GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF RESEARCH ADMINISTRATION

Date: 21 January 1970

RESEARCH PROJECT INITIATION

Project Title: Study of Design Parameters of Space Base and Space Shuttle Heat Rejection Systems

Project No.: B-1114

Project Director: Dr. William Z. Black and Dr. Wolfgang Wulff

Sponsor: NASA Manned Spacecraft Center, Houston, Texas 77058

Agreement Period: From 21 January 1970 until 20 January 1972

Type Agreement: Contract No. NAS 9-10415

Amount: $99,969

Technical Monitor

Mr. W. E. Simon
Mail Code EP5
NASA Manned Spacecraft Center
Power Generation Branch
Houston, Texas 77058

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RA-3 (4/65)

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GEORGIA INSTITUTE OF TECHNOLOGY

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RESEARCH PROJECT TERMINATION

Date: September 29, 1972

Project Title: Study of Design Parameters of Space Base & Space Shuttle Heat Rejection Systems

Project No: E-25-609 (Old B-1114)

Principal Investigator: Dr. W. Z. Black & Dr. Wolfgang Wulff

Sponsor: NASA - Manned Spacecraft Center; Houston, Texas

Effective Termination Date: August 31, 1972

Clearance of Accounting Charges: by August 31, 1972

Grant/Contract Closeout Actions Remaining:

Final Invoice & Closing Documents
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Assigned to: School of Mechanical Engineering

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RA-4 (6-71)

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

B-1114

February 5, 1970

Mr. William Simon
Power and Propulsion Division EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 1
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems".

I. General

During the first week of January, 1970, eight graduate students were interviewed and two PhD. candidates accepted as Research Assistants, in accordance with the contract. The Students are Mr. S. L. Yao and Mr. S. M. Morcos. They began work on this program officially on January 19, 1970.

The general strategy was mapped out for the system simulation. Firstly, it was decided to treat the non-linear system simulation as an initial value problem. This approach affords the uniform treatment of both the steady-state problem (Space Base) as well as the transient problem (Shuttle) and lends itself to the application of standard integration techniques. No computational instabilities or convergence problems need to be anticipated.

Secondly, it is planned to subdivide the numerical solution in elementary subtasks and to code these in subprograms. Such a structure allows great flexibility for later modifications in that only specific units need to be replaced, and it also greatly facilitates debugging of the program.

Thirdly, it was decided to develop concurrently a simplified analysis of the entire system. This analysis should serve to identify quickly relational trends between the system response and the governing parameters. It should also help to determine relative significance between overlapping transfer mechanisms.

II. Accomplishments

Six dependent variables describe the system: three fluid properties (pressure, temperature, velocity) and three temperatures (fin, tube, meteoroid protection), all as functions of time and space. The six pertinent differential equations were developed in a form suitable for computer solution (Runge-Kutta or Predictor Corrector Methods). The formulation is non-dimensional.

B 11/2/70

Computer Codes are available for the integration of simultaneous differential equations, for Simpson integration and for differentiation. A code for the solution of simultaneous algebraic equations was written and is being debugged. It will be used for solving radiosity equations.

"Direct exchange areas" for the radiative heat exchange between tube and fin were formulated and are being prepared for numerical evaluation.

The simplified system analysis was developed. The problem reduced to the solution of a single transcendental equation for the fin root temperature. A single system parameter describes the system operating conditions. The formulation of the simplified analysis seems to permit direct optimization.

A search of pertinent literature has been started. Three NASA publications and one reference manual written under a NASA contract have been collected and reviewed. The collecting of further references will be continued in future months.

A review has been initiated of appropriate relations for the Nusselt Number for laminar and turbulent flow of gases and liquids as well as liquid metals. The selected expressions will be programmed later in subroutines.

III. Future Plans

Both Dr. Wulff and Dr. Black will visit Houston sometime during the first week in March for the first of the bi-monthly progress meetings. At that time they will present their second letter report. It was anticipated that this letter report was to be delivered to Mr. William Simon during his visit to Atlanta on February 6, but his visit was canceled.

During the next month, it is anticipated that the following work will be initiated:

A study will be made to determine an appropriate expression for meteoroid protection thickness. Expressions taken from NASA publication SP-78 and TRW Users Manual ER-6792 are already under consideration.

Computer programming will be continued for numerical calculations of the fin temperature distribution and system simulation. An interpolation subroutine will be written to provide fin, and tube fluid properties from tabulated values. Direct exchange areas in terms of the geometry of the tubes and fins will be programmed.

Respectfully Submitted

W. Wulff
Co-Investigator

W. Z. Black
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WZB:lb

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

March 3, 1970

Mr. William Simon
Power and Propulsion Division EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 2
NASA Contract NAS 9-10415
"A Study of the Design Parameters of
Space Base and Shuttle Heat Rejection
Systems".

I. Accomplishments

Five subroutines have been programmed and debugged. These programs are now being tested with simulated input conditions to check their correctness. These five subroutines are particularly suited for use in the heat rejection study. They are:

1. Numerical evaluation of the first derivative.
2. Numerical evaluation of the second derivative. These two subroutines will be used for the evaluation of the discretized differential equations which simulate the performance of the heat rejection system.
3. Matrix Inversion - This subroutine will be used to determine the radiosity of each fin and tube element.
4. Interpolation routine - This subroutine will be used to evaluate coolant fluid and fin properties from tabulated values.
5. Integration by Simpson's Rule - This subroutine will be used to determine the net heat flux leaving the surface of the radiator by the radiation mode.

Equations for the direct exchange areas between tube and fin and two fin elements have been written, non-dimensionalized and checked against the results of a simplified geometry. These equations have been coded as a subroutine.

The simplified system analysis was continued. The simplified analysis is based on the one-dimensional fin and it is being used to seek an optimum number of tubes and an optimum tube length. The preliminary results indicate no optimum tube length while there is a optimum number of tubes.

The steady-state momentum, energy and continuity equations have been written for the coolant fluid so that the initial conditions for radiator operation can be determined.

Expressions for meteroid protection thickness have been reviewed. An expression for protection thickness of radiator tubes has shown that a significant portion of the radiator weight can be attributed to the protection layer. A rather large range of thicknesses can be calculated depending upon the degree of conservatism of the designer.

II. Future Plans

The simplified analysis will be continued in search of other radiator properties and geometries which will contribute to an optimum design.

The expressions for the direct exchange areas will be debugged.

Properties of several fin materials and coolant fluids will be tabulated for future use in the governing differential equations.

The expression for meteroid protection thickness will be programmed and debugged. A search of more recent literature will be undertaken for the purpose of finding reliable values for experimental constants which are used in the expression for protection thickness.

Respectfully Submitted,

W. Wulff
Co-Investigator

W. Z. Black
Co-Investigator

S.P. Kezios, Director 3-4-70
School of Mechanical Engineering

WZB:lb

File

GEORGIA INSTITUTE OF TECHNOLOGY

ATLANTA, GEORGIA 30332

April 1, 1970

SCHOOL OF
MECHANICAL ENGINEERING

Mr. William Simon
Power and Propulsion Division EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 3 NASA Contract NAS9-10415 "A Study of the Design Parameters of Space Base and Shuttle, Heat Rejection Systems."

I. Accomplishments

The five subroutines written last month and described in Letter Report No. 2 have been checked out successfully.

A complete system of heat rejection materials has been selected so that their thermophysical properties may be tabulated and programmed as subroutines. The system consists of:

1. Tube and fin material: copper or aluminum
2. Meteroid protection material: Beryluim
3. Coolant fluid: liquid - Dow Corning 200
   gas - Nitrogen
   liquid metal - NaK

At the present time the properties are being accumulated for these materials. Power polynomials and other suitable functions are being fitted to represent the property data where this is feasible. Other property data will be numerically interpolated (Aitken algorithm) by a subroutine written and successfully tested for this purpose.

A program has been written for the solution of the coolant fluid energy, continuity and momentum equations. This program will provide the initial conditions for the governing differential equations of transient heat transfer.

A subroutine for the meteroid thickness has been written and is presently being debugged.

The subroutine for the exchange areas between the fin and tube and two adjacent fin elements has been written and debugged. A special case of an infinitely long fin is being used to check the accuracy and validity of this program.

A short explaination of the contents and the theory behind the simplified analysis is included in this report. Although a simplified analysis was not a part of the contract, we are happy to provide details concerning its operation.

II. Future Plans

In the coming month the governing differential equations will be programmed to provide time derivatives of the fin temperature, tube temperature, meteroid protection temperature and coolant fluid properties.

The control program will be written and tested. The purpose of the control program will be to provide output and to terminate the integration process.

A subprogram will be written that will calculate the radiosity from each fin and tube element. This program will be used to evaluate the net radiant energy leaving each radiator element.

Respectfully submitted,

W. Wulff
Co-Investigator

W. Z. Black
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WW/jt

File

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

May 1, 1970

Mr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 4
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems"

I. Accomplishments

The subprogram for all six of the governing differential equations has been coded. The program includes the appropriate boundary conditions.

The subprogram which calculates the meteoroid thickness has been completed and successfully tested .

Power polynomials have been fitted to a total number of twelve properties as functions of the system temperature (and pressure or density in the case of coolant fluid properties). The curves for the following properties have been evaluated and punched on cards:

1. Coolant fluid properties for 1CS Dow Corning 200
   Thermal conductivity as a function of temperature
   Dynamic viscosity as a function of temperature
   Specific heat at zero pressure as a function of temperature.

   The reference used for these properties is ASME Research Publication, Pressure-Viscosity Report Vol. II 1953

2. Fin properties for aluminum and copper and meteroid protection properties for berylium
   Thermal Conductivity k as a function of temperature
   Specific heat c as a function of temperature
   Modulus of elasticity as a function of temperature.

   The reference used for k and c is Thermophysical Properties Research Center, Purdue University, Vol. and Vol. 2, Part II, Y. S. Touloukian, Editor.

   The reference used for the modulus of elasticity data is TRW Property Data for Space Radiator-Condenser Design, Prepared under contract NAS 9-4884 April 1966.

The following units have been selected for several properties They will be used consistently throughout the program.

dynamic viscosity	lbf hr/ft^2
velocity	ft/hr
thermal conductivity	Btu/hr ft R
specific heat	Btu/slug R
density	slug/ft^3

A subprogram for the evaluation of the radiative heat transfer between fin and tube as well as between fin, tube and other radiatively active surfaces has been formulated and coded. This program utilizes two previously written subprograms, the program for the radiative exchange areas and the matrix inversion program.

II. Future Plans

The subprogram to evaluate the net radiant energy leaving each fin and meteoroid protection layer element will be continued.

The subprograms for all six governing equations will be checked and tested under simulated conditions.

An equation of state for Dow Corning 200 will be derived and programmed. The equation will be developed from the data of the isothermal compressibility and bulk modulus of the fluid.

A main program will be written which will call all property subroutines and check each property for strategic choices of pressure and temperature. The property value returned by the subroutine will be compared with values taken from references.

Respectfully submitted,

W. Wulff, Co-Investigator

W. Z. Black, Co-Investigaor

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WZB:lb

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

June 1, 1970

Mr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 5
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems"

The major accomplishments of this project to date were outlined in a meeting held at MSC on May 27, 1970.

During the meeting it was decided to:

1. Use the 026 key punch exclusively.

2. Develop two main programs for the Calcomp plotting, one for the MSC and one for the Georgia Tech installation.

3. Consider Z93 as the surface coating material. Optical properties are available from Wright Patterson AFB reports, publications of Atomic International and of NASA Lewis.

4. Utilize existing computer programs for the treatment of the external radiant heat flux, Midwest Research Programs, and for the convective heating during ascent and re-entry, MSC Aerodynamics Section. Data transfer through cards or magnetic tape is acceptable.

Accomplishments

Work is continuing on programs for the six governing differential equations, for the fluid properties, for radiant flux and for the equation of state of the coolant fluid.

The programs for the thermal conductivity, specific heat, modulus of elasticity and the temperature variation of thermal conductivity for the fin, tube and protection material have been completed. The programs for the isobaric thermal expansion coefficient, isothermal compressibility, dynamic viscosity, thermal conductivity and specific heat of the coolant fluid have been completed.

Future Plans

The development of the program to calculate radiant flux leaving each fin and protection element will be continued.

The two parts of the subprogram for the six differential equations will be combined after each part has been thoroughly checked.

Property subroutines for the surface coatings will be initiated. The properties sought will be hemispherical infrared emittance and hemispherical solar absorbtance.

The preparation for using NASA programs for external heat flux on the shuttle radiator system during ascent and re-entry and incident radiant flux on the space base radiator will be started.

Respectfully submitted,

W. Wulff, Co-Investigator

W. Z. Black, Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WZB:lb

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

June 29, 1970

Mr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 6
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems"

Accomplishments

The derivative subprograms which evaluate the time derivatives of the system parameters have been completed and are being checked out.

Significant portions of the Main program and the Control subprograms have been written. Further progress has been made in the coding and testing of the Radiant Flux subprogram. The functions of these routines have been explained in our Letter Reports No. 3 and 4.

Work is continuing on the property subprograms. During the past month two property subprograms for Dow Corning 200 were coded and checked. They are: thermal conductivity as a function of temperature and dynamic viscosity as a function of fluid density and temperature. A third program for the specific heat at constant pressure has been coded but not checked. Reference material for the optical properties of surface coatings has been collected.

A literature search is being carried out in the course of developing and aerodynamic heating model for the ascent and descent phases of the shuttle simulation.

Future Plans

Work will be continued on the Radiant Flux and the property subprograms.

The Control, Main and Derivative subprograms will be combined and checked.

Further effort will be spent on the development of a suitable model for aerodynamic heating.

Respectfully submitted,

W. Wulff, Co-Investigator

W. Z. Black, Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WZB:lb

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

July 29, 1970

Mr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

SUBJECT: Letter Report No. 7
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems".

Accomplishments

All programs previously punched with the 029 keypunch have been converted to the 026 keypunch.

The subprogram for Dow Corning 200 properties have been coded and successfully checked. This subprogram consists of the following eight properties all as a function of density and temperature: dynamic viscosity, thermal conductivity, pressure, isothermal compressibility, isobaric expansion coefficient, specific heat at constant pressure, enthalpy and

$\frac{1}{K}\left(\frac{dK}{dT}\right)$.

Work on the RADIANT FLUX subprogram has continued.

The CONTROL, MAIN, INITIALIZATION, and DERIVATIVE subprograms have been combined. Preliminary test runs involving the Runge-Kutta Integration have been executed. Further diagnostic runs are necessary. The output of transient variables in tabular form has been coded and successfully tested.

A preliminary aerodynamic heating model has been selected. Upper surface heat transfer coefficients reported by F. L. Guard and H. D. Schultz in ASME paper 70-HT/SpT-16 entitled "Space Shuttle Aerodynamic Heating Considerations" will be used. Atmospheric properties to be used in this portion of the program are presently being coded. Ascent and reentry convective heating loads provided by this model will be compared with the ones given by the SMD analysis before the final model is selected.

Future Plans

Work will continue on the aerodynamic heating and radiant flux subprograms. Properties for the coolant fluid helium will be coded. The skeleton form of the final program will be checked out further. Subroutines will be added to the final program only after the final program has been thoroughly checked.

Respectfully Submitted,

W. Wulff, Co-Investigator

W. Z. Black, Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WZB:1b

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

August 31, 1970

Mr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 8
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space
Base and Shuttle Heat Rejection Systems

Accomplishments

The aerodynamic heating subprogram CONVEC has been coded. Both laminar and turbulent flow Nusselt numbers are calculated within this subprogram. A separate subprogram ATMOS which calculates atmospheric properties to be used in the CONVEC subprogram has been coded and checked. The properties used in ATMOS were taken from the 1962 Standard Atmosphere. CONVEC provides a Nusselt number for each fin and meteroid protection nodes for both ascent and reentry of the shuttle vehicle.

Work on the RADIANT FLUX subprogram has continued. This subprogram now accounts for partial overlap of the fin by the meteroid protection layer. Incident flux values for sun, earth and earth albedo given by the Midwest Research Program are presently being prepared for use with RADIANT FLUX program.

Further progress has been made on the integration of the CONTROL MAIN, INTIALIZATION and DERIVATIVE subprograms. Computations made within the DERIVATIVE subprogram have been checked, but further refinement of the main integration is needed. Parts of the METEROID PROTECTION subprogram have been incorporated into the integrated program.

Programs for the equation of state, isothermal compressibility and isobaric expansion coefficient for Helium have been programmed. The equation of state program has been checked.

Future Plans

Work will continue on the aerodynamic heating and radiant flux subprogram.

The remaining properties for Helium will be programmed.

Further testing and checking of the assembled program will be carried out. Other subprograms will be incorporated into the assembled program as they are completed and tested.

Respectfully submitted,

W. Wulff
Co-Investigator

W. Z. Black
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WZB:lb

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GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

October 30, 1970

Mr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 10
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems."

Accomplishments

The check out of the PROPERTY subprogram for the coolant fluid Helium has been completed.

Work has begun on coding the optical properties for Z 93 which is to be used as a thermal control surface coating. Inspite an intensive literature search, no data on the temperature dependence of solar absorptance and infrared emittance could be found so far. We would appreciate any data provided by MSC while we shall continue to search for possible sources.

Properties of the atmosphere, required for the calculation of aerodynamic heating and coded in a subroutine called ATMOS, have been extended from an elevation of 300,000 feet to 500,000 feet. The properties for the extended range were taken from the latest issue (1966) of the U. S. Standard Atmosphere. Atmospheric properties returned by ATMOS have been checked for altitudes less than 300,000 feet as reported in Letter Report No. 8. Properties for altitudes greater than 300,000 feet are presently being checked.

The caculation of shuttle velocity and altitude as a function of time have been incorporated into subprograms called VELSH and ATLSH respectively. Presently velocity and altitude data supplied by MSC are being used as typical flight profiles. These data are read into the program in array form in order to accomodate any arbitrary flight profile.

Work has continued on the RADIANT FLUX subprogram.

The subprogram DERIV has been incorporated into the integrated program. There remains the phasing in of the subroutines for subprograms which supply the radiant flux (QRAD) and the convective flux (CONVEC).

Further modification and checkout of the integrated program has been carried out. A typical output of the integrated program is included with this Letter Report.

Future Plans

Work will continue on the RADIANT FLUX and CONVEC subprograms. Coding of the optical properties of Z 93 will be continued. Once these properties have been coded and thoroughly checked, coding of the properties of the coolant fluid NaK will be initiated. Further modification of the integrated program will be made as completed subporgrams are added to it.

Respectfully Submitted,

W. Wulff
Co-Investigator

W. Z. Black
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WZB:lb

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

December 2, 1970

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 11
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems."

Accomplishments

All properties for the coolant fluid NaK have been coded and successfully checked. All computed property values deviate no more than 1.2% from the referenced values for temperatures ranging between 200F and 1400F.

Work has continued on the radiant flux subroutine (QRAD). The previously coded interpolation routine (YINT) serves to evaluate, at any time step, the incident radiant flux values from the results of MRI program.

Work has continued on the convective heating subroutine (CONVEC). A separate subroutine (NUS) called within CONVEC has been written to evaluate the Nusselt number for both free and forced, laminar and turbulent flow regimes. The check out of the subroutine NUS is in its final stages. When this subroutine has been completely checked, the subroutine CONVEC will be mated with the integrated program.

The major derivative subprogram DERIVM for the main integration is completed and checked. A lumped-parameter computing feature has been included for the computation of the conduction through the tube wall and the meteroid protection layer. This computing feature reduces the computing time considerably in the case of low Biot numbers.

Future Plans

The two subroutines QRAD and CONVEC will be added to the integrated program. Further checking of the integrated program will then be necessary.

Work will continue on the coding of the thermophysical properties of the surface coating Z93. The emittance and absorptance values for Z93 will consist of single values at infrared and visible wavelengths and they will be temperature independent. A further literature search carried out in the past month has not produced the temperature dependence of emittance or absorptance.

A large percentage of the effort during the month of December will go towards the writing of the final report for Phase I.

Respectfully submitted,

W. Wulff
Co-Investigator

W. Z. Black
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WZB:lb

B1114

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

December 30, 1970

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

SUBJECT: Letter Report No. 12
NASA Contract NAS 9-10415
"A Study of Design Parameters of Space Base and Shuttle Heat Rejection Systems".

Accomplishments

The set of subprograms design to compute the aerodynamic heating during both the ascent and reentry has been completed and prepared for inclusion in the main deck assembly.

The set of subroutines for the computation of the radiant heat flux from the fin and flow channel has been modified to allow the mapping of different grids for the computation of the fin temperature distribution (fine grid) and of the radiant heat flux distribution (coarse grid). This set of subroutines is also completed and prepared for inclusion into the main deck assembly.

Several checks for internal consistency within the main integration have been carried out, based on local and global conservation of energy. The results are also being compared with the simplified analysis developed earlier in the program.

The coding of the optical properties of the surface coding Z93 is completed.

The major portions of the final report for Phase I have been drafted.

Future Plans

The month of January will be devoted to the completion of the final report, to the execution of several test runs and to a literature survey of appropriate optimization techniques. The simplified analysis will be further developed for the purpose of supporting the optimization.

Respectfully submitted,

W. Z. Black
Co-Investigator

W. Wulff
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

~~WZB~~ WW:lb

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

February 4, 1971

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 13
NASA Constract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems."

Accomplishments

A draft of the final report for Phase I has been completed. A complete rough draft copy has been typed and typing of the final copy has started.

A final check of the aerodynamic heating program as well as other internal checks on the main deck assembly have been completed.

All nondimensional groups used to describe the performance of the radiator system have been assembled. Selected groups will be used as descriptive parameters during the optimization phase of the study.

Future Plans

A small amount of work will be needed for the completion of the final report for Phase I. Work will also continue on the selection of proper optimization techniques to be used during Phase II.

Respectfully submitted,

W. Z. Black
Co-Investigator

W. Wulff
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WW/WZB:jkt

LIBRARY DOES NOT HAVE LETTER REPORT # 14

GEORGIA INSTITUTE OF TECHNOLOGY

ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

April 5, 1971

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 15
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems."

Accomplishments

The major accomplishments of the project during Phases I, II and III were summarized in a year end report presented at MSC on March 23, 1971. In addition to the year end report , separate meetings were held with Mr. John Orsag concerning the MRI program, Mr. Robert Dotts and Mrs. Dott Lee concerning the aerodynamic heating model and Mr. B. G. Cour-Palais concerning the meteoroid protection model.

During the meeting with Mr. Orsag, it was decided that the MRI program will be run for expected flight profiles and irradiation data will be stored on magnetic tape. These data will be entered into the assembled program as a tape input. In this regard the irradiation data supplied by the contractor has been successfully transferred to a Georgia Tech tape, called and printed out.

Ascent and reentry orbiter profiles supplied by Mrs. Lee of the Structures and Mechanics Division on March 23 have been used to generate a more recent convective heating rate for the orbiter vehicle. Comparisons are presently being made between these heating rates and those predicted by the SMD's unit sphere method.

The meeting with Mr. Cour-Palais produced general agreement between MSC's most recent meteoroid protection model and the model presented within the Phase report; however a modified model based on the Brinell hardness of the meteoroid protection material was suggested and the ranges of several empirical constants were modified.

The subprogram for the enthalpy of helium (HFL), which was not delivered at the time of the year end report, has been run and tested. A copy of this subprogram is included with this Letter Report.

The improved simplified analysis reported in last months Letter Report has been coded and tested successfully.

Future Plans

The assembled version of the program will be modified in an attempt to reduce the computer run time. The subprograms which evaluate the convective and radiative heat fluxes from the radiator system will be tested separately and modified in an attempt to significantly reduce the number of times these subroutines are called, and also the time required for computation within these subprograms.

Respectfully Submitted,

W. Z. Black
Co-Investigator

W. Wulff
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WW:WZB/lb

GEORGIA INSTITUTE OF TECHNOLOGY
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SCHOOL OF
MECHANICAL ENGINEERING

May 6, 1971

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 16
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems."

Accomplishments

The major accomplishments during the month of April were summarized in a meeting held at Georgia Tech with Dr. Simon on April 26 and 27.

The results of the simplified analysis indicated that close tube-spacing and consequently significant radiative interactions between adjacent tubes and between tube and fin are associated with optimum radiator configurations. The simplified analysis was therefore modified to account for radiation from the flow channels and for the partial blocking of the radiant heat flux from channels and fins. This modification has been programmed and successfully tested.

The large-scale computer program optimization has been continued. Simplifications are being incorporated in the most time-consuming sub-programs.

The shape factor subroutine is being modified to include the tube-to-tube and the tube-to-far fin interactions; the view factor for the latter interaction has been coded and is being checked.

The aerodynamic heating model has been run for the cold wall case using the reentry and ascent profiles supplied by the Structures and Mechanics Division. A comparison of these results and those of SMD's unit sphere method are shown on the curves attached to this Letter Report.

The aerodynamic heating programs have been streamlined and simplified in order to minimize computer run time. The calculation required for a heating profile have been reduced by 50% with a resulting difference between the results of the old and new analysis being no greater than 0.75%.

Work has begun on the task of placing the entire program on FASTRAN. The programs necessary for entering the program on the drum, subdividing it into working units, and combining the units into several frequently used versions have been coded and punched. These FASTRAN decks will be included with the other programs that are to be submitted to the contractor at the time of the year end report.

Future Plans

Work will continue on efforts to further reduce the computer run time particularly in the programs for the calculations of the radiant flux.

The program modification for the shape factor will be checked and integrated into the main program.

The work required to place the entire program on FASTRAN will continue.

The effort to find radiator geometries which lead towards an optimimum heat loss per unit weight by using the simplified analysis will be continued.

Respectfully Submitted,

W. Z. Black
Co-Investigator

W. Wulff
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

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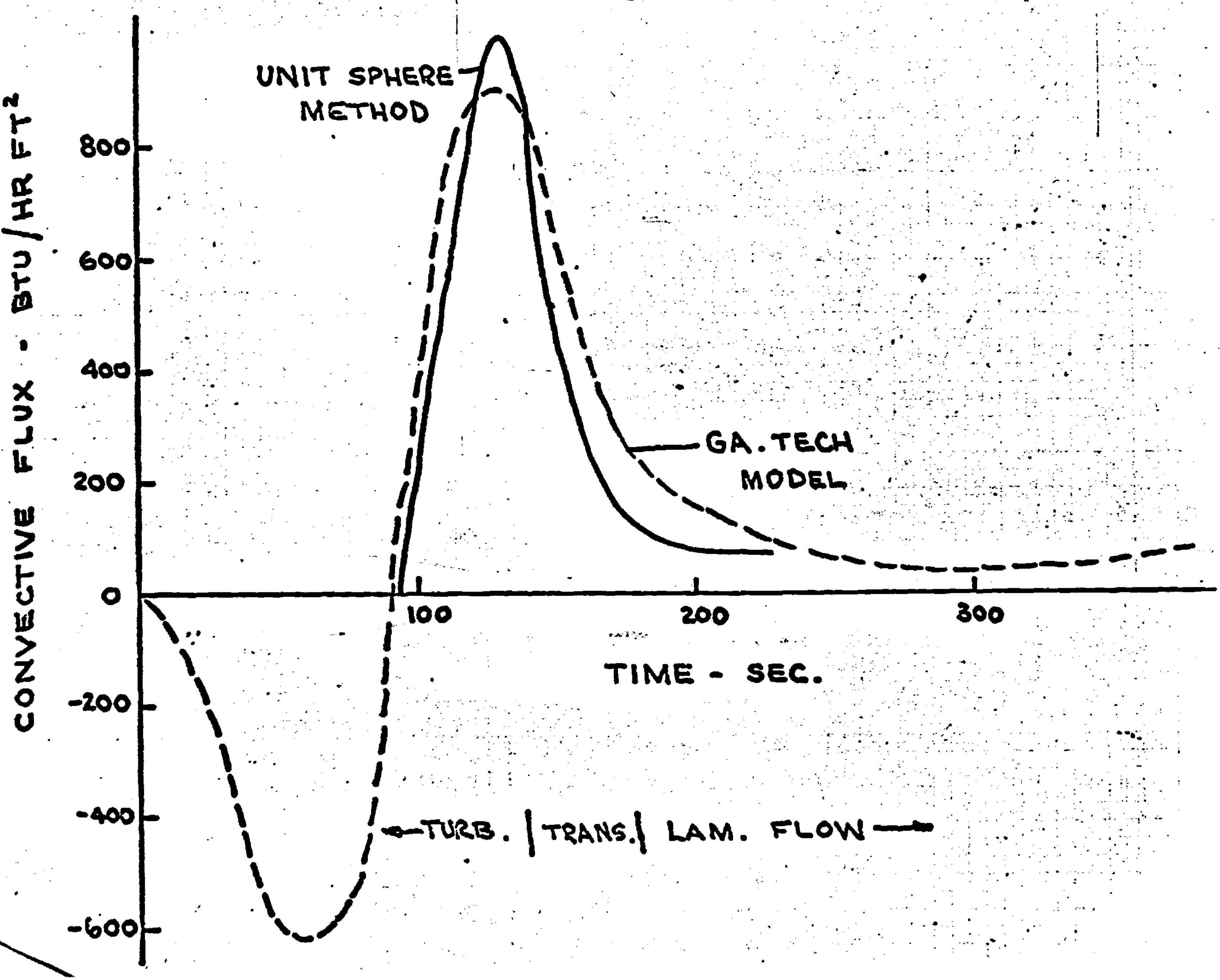
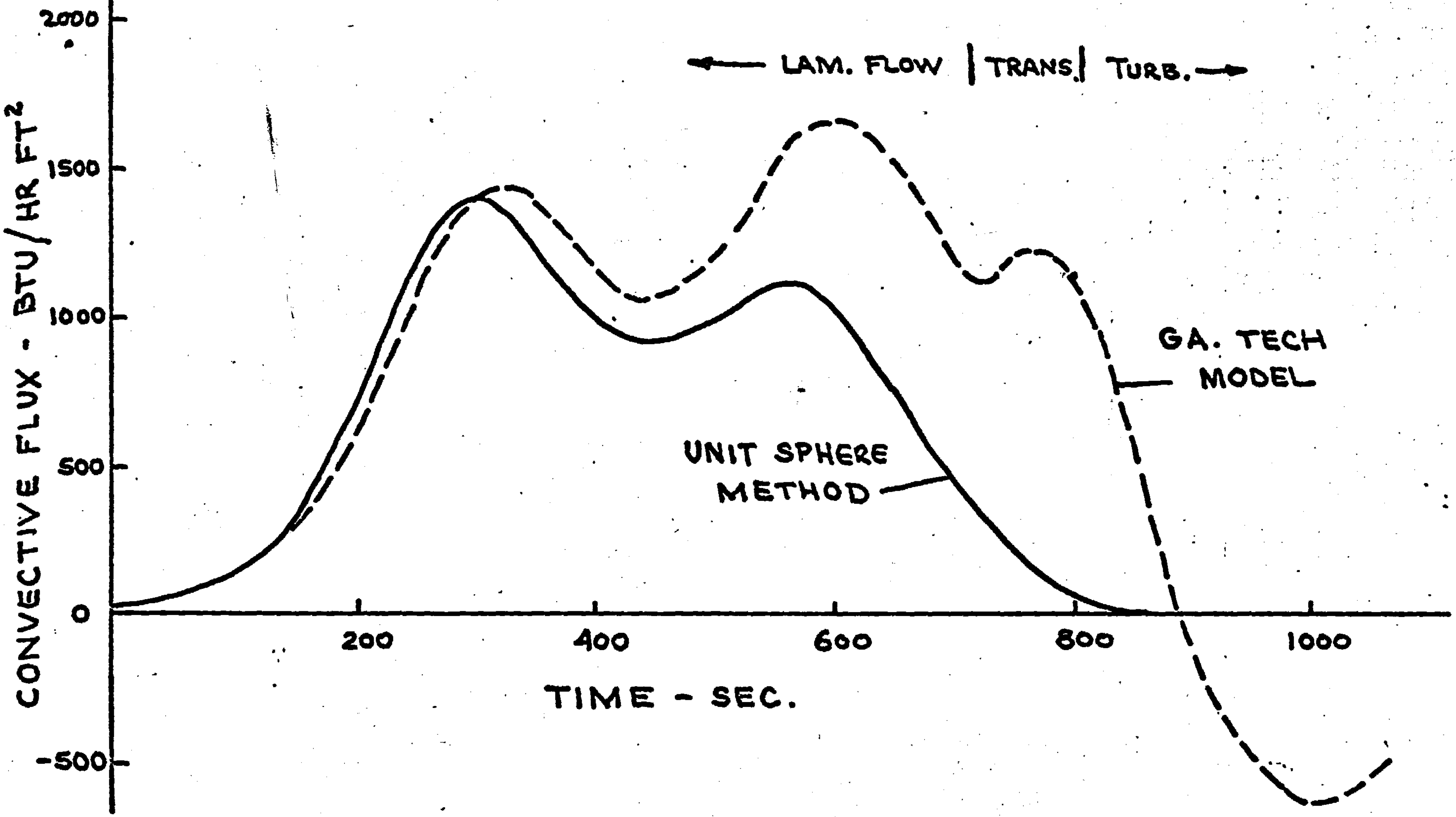
ASCENT HEATING PROFILE
COLD WALL



REENTRY HEATING PROFILE
COLD WALL



GEORGIA INSTITUTE OF TECHNOLOGY
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SCHOOL OF
MECHANICAL ENGINEERING

June 7, 1971

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 17
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems."

Accomplishments

Expressions have been written for the thermodynamic properties of the two 3-M Company coolant fluids FC-75 and FC-43.

Expressions for the shape factor between two elements on adjacent fins and for elements on adjacent tubes have been written and coded. The expression for the former has been checked.

The subprograms used to calculate the net radiant flux from the radiator system have been studied for possible ways to decrease the computation time. The shape factor subroutine execution time has been reduced by a factor of five.

The streamlining of the convective flux subroutines has been completed. A final reduction in the computation time of approximately 10% has been realized, so that the present computation time is about 40% of the original run time before simplification. The total time required to compute the instantaneous convective flux is now approximately 100 milliseconds.

As outlined in the Annual Report, the program has been separated into a permanent deck, property decks and a data deck all of which have been loaded on FASTRAN drums. Checks are presently being made between the results produced by the FASTRAN decks and results previously produced from card images.

Future Plans

Work required to reduce the run time of the radiation subroutines will continue.

The property programs for the coolants FC-75 and FC-43 will be coded and checked. The shape factor program for tube to tube exchange will be checked. The work on the FASTRAN decks will be completed.

A study will be started to find the location of the adiabatic plane which separates two tubes with unequal fluid temperatures and two neighboring fins with unequal incident radiant flux. If the location of such a plane is known, then the original program may be modified to allow more flexibility, because it may then be used to study cases where two adjacent coolant channels are not fed by a common manifold.

The effort to find radiator geometries which lead towards optimum heat loss will be continued.

Respectfully submitted,

W. Z. Black
Co-Investigator

W. Wulff
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

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CC: Mr. Martial Davoust

Ⓑ 1119/Black

GEORGIA INSTITUTE OF TECHNOLOGY
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SCHOOL OF
MECHANICAL ENGINEERING

July 7, 1971

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 18
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems."

Accomplishments

The thermodynamic properties for the two coolant fluids FC 43 and FC 75 have been coded and checked. The resulting property subroutines have been loaded on FASTRAN drums.

The work on the FASTRAN decks has been completed with all existing program elements loaded on FASTRAN drums. Several preliminary checks have been made between the output produced from the card images and the FASTRAN decks. More extensive runs and comparisons involving realistic input parameters suggested by Dr. Simon will be made in the coming months.

The effort to reduce the computation time required in the radiant flux subprograms has been completed.

The cause of unrealistic oscillations in the fin radiosity has been traced to the evaluation of the shape factor between tube and fin elements closest to the tube. Since the shape factor between closest pairs of elements is typically several orders of magnitude larger than any other shape factor, the integration necessary for the determination of the radiant flux resulted in sizeable truncation errors. The current shape factor analysis replaces the local value with a mean value and as a result the oscillation in radiant flux has disappeared. The differential view factor integrated along the tube, including the mean value result, checks within a fraction of one percent of the shape factor for a fin element with respect to all of the tube. Expressions for all shape factors have been completely checked. The shape factors evaluated in the subroutine SHAPEF are now:

1. Tube to adjacent fin.
2. Tube to far fin.
3. Tube to tube.
4. Fin to adjacent fin.

The simplified analysis has been extended to account for the blockage or radiant energy by the tubes. As a result the analysis now requires four parameters rather than three for the specification of the system geometry.

Future Plans

The analysis started last month for the location of the adiabatic plane separating two flow channels with unequal fluid temperatures will be continued. Work to date has concentrated on two cases. The first case involves a single flow channel which forms a "U" shape and encloses a fin element. The second case is that of a fin element which separates two channels which have known, but different, inlet temperatures and flow rates.

Work will continue on the simplified analysis and on the determination of operating conditions for a series of anticipated input parameters. The simplified analysis will be used to select areas of operating conditions which appear to lead towards optimum operation.

Respectfully submitted,

W. Z. Black
Co-Investigator

W. Wulff
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

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CC: Mr. Martial Davoust

GEORGIA INSTITUTE OF TECHNOLOGY
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August 3, 1971

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 19
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems."

Accomplishments

Modifications to the assembled program are being made so that output can be obtained when the coolant fluid is assumed to be incompressible. The original program encounters division by zero whenever the isothermal compressibility is set equal to zero. This situation occurred for the first time when the incompressible fluids FC43 and FC75 were used.

Global energy balances are being made on radiator system as a check on the output data of the assembled program.

Several sections of the final report have been written. These sections include: thermodynamic properties of the coolant fluids FC43 and FC75 and the development of the shape factor between two adjacent tubes, between two elements on adjacent fins and between the tube and an element on the far fin.

The values for incident solar flux and earth albedo have been added to the computer printout when the radiator system is in orbit.

As reported in Letter Report No. 18 a separate program has been written for the determination of the location of the adiabatic plane separating two flow channels which are connected to two different manifolds. This program, called ADIABH, has been coded and is presently being checked.

Work has continued on the modifications to the Simplified Analysis and on the optimization programs. Six additional, ordinary, first-order differential equations were developed and coded and are being checked to produce the rates of change of coolant exit temperature with respect to three non-dimensional fin system parameters. These rates indicate which parameters affect the system performance most effectively. These rates must also be zero at an optimum.

Future Plans

In the next several months the major portion of the effort will be concentrated on the Simplified Analysis and the optimization techniques. Production runs will be made from the remote terminal.

Respectfully submitted,

W. Z. Black
Co-Investigator

W. Wulff
Co-Investigator

Approved:

S. P. Kezios, Director
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GEORGIA INSTITUTE OF TECHNOLOGY
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September 9, 1971

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 20
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems."

Accomplishments

The program ADIABH reported in Letter Report No. 18 has been completed and checked.

Further checks of the main program output have been made. Global energy balances on the fin system have uncovered several program errors. Corrections have been made on the computer cards and on the programs stored on FASTRAN drums.

Work has begun on the selection of reasonable input variables so that production runs may be made. These runs will be made from the remote terminal once the checks of the global energy balances produce consistent results.

The development of the optimization has been continued and the influence coefficients of the radiator performance with respect to the geometric system parameters are coded and checked out. Work has begun on the Newton-Raphson algorithem used to seek the geometric parameters of optimum performance.

Future Plans

Work on the simplified analysis and the optimization techniques will continue.

The program will be modified to accept tape input data from the MRI program. Presently incident solar and infrared flux values are read in as program input. These read statements will be removed and the program modified to read this data from taped output of the MRI program.

Respectfully submitted,

W. Z. Black,
Co-Investigator

W. Wulff
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WW/WZB:1b

CC: Mr. Martial Davoust

GEORGIA INSTITUTE OF TECHNOLOGY
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SCHOOL OF
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October 5, 1971

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 21
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems."

Accomplishments

Checks of a global energy balance applied to the fin system have uncovered several program errors which have been corrected.

Rough drafts of two sections of the final report have been written. These sections include the description of the program ADIABH which serves to compute the location of the adiabatic plane between adjacent tubes with non-symmetric flow conditions and the formulation of additional shape factors which were not included in the final report submitted at the end of the first year.

The subroutine QINCID has been modified so that incident radiant flux data may be entered into the program from cards or from tapes. The tape input option will allow irradiation data to be transferred from the MRI program. The format of the tape data was assumed to be identical to that of the sample tape given to Georgia Tech earlier this year with one exception. A group number must be supplied to each data set so that the proper data set may be selected from several groups that may be stored on the tape.

At the time of modifying QINCID, the number of flux values that must be specified for each side of the tube has been increased from three to six. It is felt that this increase will lead to a more representative value of the incident flux on the tube.

A print-out copy of the simplified analysis program and a description of the program operation are being prepared and they will be given to Dr. Simon in a meeting to be held in Houston within the next month.

Optimization on the basis of the simplified analysis has been continued.

Personnel changes took place on Sept. 20, 1971 as follows: Mr. W. W. Carr, a Ph.D. candidate and Mr. J. R. Huntley, a M.S. student, were added to the project. Mr. S. L. Yao is returning to Taiwan and is no longer employed on the contract.

Future Plans

Work will continue on the simplified analysis and the optimization program.

The program ADIABH will be modified to accept incident flux data from tape.

Fastran decks will be assembled and will be given to Dr. Simon in this month's meeting if they are completed by that time.

Production runs will be started when the remaining internal program checks have been completed.

Respectfully submitted,

W. Z. Black
Co-Investigator

W. Wulff
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

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E-25-609

GEORGIA INSTITUTE OF TECHNOLOGY
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November 3, 1971

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 22
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems."

A progress meeting was held in Houston on October 20, 1971. Present were T. Redding, W. Dusenbery, W. Chandler, W. Simon, W. Black and W. Wulff. A brief summary of the progress made to date and the current status of the contract were given. The contents of the new simplified analysis were discussed and a copy of the program was given to Dr. Simon. Later a test run of the simplified analysis was made.

During the meeting the adaptability of the program to physical cases that deviate from the basic geometry of the original analysis were discussed. Priorities were established on work to be completed in the future. These priorities were:

1. Provide for incident fluxes to be read from a MRI tape to be supplied by the contractor.

2. Integrate the separate program ADIABH into the main program so that individual runs are not necessary.

3. Expand the use of the program ADIABAH to cover a "U" shaped tube and more than two adjacent, asymmetrically loaded tubes.

4. Modify the main program to accept fluid inlet temperatures and mass flow rates that vary with time.

The possibility of a no cost extension to the contract was discussed. The co-investigators were asked to determine the number of man-months of funding that will be left in the contract budget if the present funding level is continued. The co-investigators were also asked to determine how far they would be able to proceed through the priority list before the present contract expired.

The co-investigators intend to submit a letter in the near future requesting a no cost extension of the contract. There will be funds remaining in the budget to support the current effort for 60 additional days plus 30 days for the writing of a final report beyond the expiration date of the present contract. The letter will also include the goals to be achieved during the extension period. The co-investigators also intend to complete the first item on the list of priorities above before the contract expires. The remaining three items will form the basis of the work to be completed during the extension period.

Accomplishments

Work has already begun on the insertion of the MRI flux data into the main program. The Georgia Tech program has been modified to accept MRI input from magnetic tape as was reported in Letter Report No. 21. Changes in the program logic are being made so that shadowing of the tube by the fin will be accounted for in the Georgia Tech program. The program assumes that the flux output for the n-sided polygon specified by the MRI program has the fin orientated so that it is attached to the polygon between the surfaces labeled as 1 and n. Further modifications of the Georgia Tech program will produce consecutive runs for a curved radiator panel if the user supplies the angles between the normal to the fin elements.

The separate program ADIABH now accepts flux data from the MRI program. Whenever two adjacent fin elements are not in one plane, the program assumes that the fin radiates only from the convex side of the fin and the concave side does not radiate.

Another section of the final report has been written in rough draft form. The section describes the FASTRAND program and it also gives several examples of FASTRAND programs with the resulting output.

The internal program checks that were first reported in Letter Report No. 19 are being continued. Separate energy balances on the tube, fluid and fin have been completed. Additional runs have been made so that more detailed output may be obtained and the terms of energy balances checked more thoroughly. As a result of these energy balances, the various energy terms determined by a desk calculator check within a few percent of the computor results under both transient and steady state cases.

The program output has been modified to include two additional terms: the energy stored in the radiator panel and the energy conducted into the fin from both the inlet and exit manifold.

Future Plans

Future work will concentrate on the optimization program, on the effort to integrate the MRI program and on the check of the internal energy balances.

Respectfully submitted,

W. Z. Black
Co-Investigator

W. Wulff
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WW:WZB/lb

CC: Mr. Martial Davoust

E-25-609

GEORGIA INSTITUTE OF TECHNOLOGY
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SCHOOL OF
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December 15, 1971

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 23
NASA Contract NAS 9-10415
"A study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems."

Accomplishments

The internal program checks first reported in Letter Report No. 19 have been continued. A detailed check of the terms in the energy equation for the coolant fluid has indicated that the truncation error in the equation for the time rate of temperature change for the first tube element is too large to represent the local axial temperature drop in the fluid. This equation has been modified and it is presently being checked.

The optimization program based on the simplified analysis has been continued. Sixteen of the eighteen derivatives of the outlet fluid and fin base temperatures with respect to the design parameters U, V, $\overline{N}_c$ have been programed and completely checked.

The MRI program has been integrated into the main program. Test cases have been run which read incident flux data from an MRI tape.

Future Plans

The final two derivatives needed to complete the optimization technique will be programed and checked.

The program to extend the application of ADIABH to cases of more than two parallel tubes or counterflow through two or more "U" shaped tubes will be initiated.

Respectfully Submitted,

W. Z. Black
Co-Investigator

W. Wulff
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WZB:jp

E-25-609

GEORGIA INSTITUTE OF TECHNOLOGY
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SCHOOL OF
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January 6, 1972

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 24
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space
Base and Shuttle Heat Rejection Systems."

Accomplishments

The expansion of the subprogram ADIABH listed as item #2 in the letter to Dr. Simon dated Nov. 12, 1971 which itemizes the goals of the no-cost extension of this contract has been started. The work completed to date involves the formulation of equations which will extend the use of ADIABH beyond the present two parallel tube cases to one involving an arbitrary number of parallel tubes which are either straight or U-shaped.

The subprogram QINCID which averages the radiant flux over the flow channels and acts as a transfer point between the MRI and main program has been modified so that incident fluxes may be calculated for a radiator panel that does not lie in one plane. The curved panel is assumed to be composed of a series of continuous plane segments. The user is expected to supply angles between the normals to the adjacent plane segments as program input. Test runs have been made of these modifications and the results have been completely checked.

The modification to the coolant fluid energy equation for the first tube element reported in Letter Report No. 23 has been made. This modification has resulted in some improvement in the global energy balance for the entire radiator system, but a difference between the steady state energy leaving the system by radiation and the energy lost by the coolant fluid of approximately 20% still remains. Modifications to the energy equations will be continued to obtain internal consistency in the energy balance.

All but two derivative programs needed for the optimization have been completed and verified.

Future Plans

The above mentioned modifications to the subprogram ADIABH will be programmed and checked.

The work on the optimization program and on the program changes necessary to achieve consistency checks of the global energy balances will be continued.

Respectfully Submitted,

W. Z. Black
Co-Investigator

W. Wulff
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

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cc:Mr. Martial Davoust

E-25-609

GEORGIA INSTITUTE OF TECHNOLOGY
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SCHOOL OF
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February 8, 1972

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 25
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems."

Accomplishments

Internal program checks of the global energy balance have indicated large truncation errors in the temperature field calculation at the tube-manifold intersection, as a result of fluid inlet temperature changes. The program was modified to treat the entire fluid flow field quasi-statically rather than only the velocity and pressure fields. This allows for better fluid and tube wall temperature coupling resulting in a more gradual decrease in the coolant fluid temperature near the inlet to the tube. The modifications are justified because the fluid residence time is small compared to the equilibration period of the radiator system.

The final two derivatives of the coolant fluid temperature that are used in the optimization program have been coded and checked. A Newton-Raphson technique has been coded and is being verified to iterate toward system parameters that result in maximum heat rejection for the constraint of constant system area.

The programming of ADIABH for cases of more than two parallel tubes has been completed and checked. The current version of the program is limited to ten adjacent tubes although this restriction may be easily relaxed. Any combination of coolant flow rates, inlet fluid temperatures and sink temperatures which lead to a condition for which there is no adiabatic interface is identified with diagnostic print-out. This situation does not produce a fin system which adheres to the boundary conditions of the present program.

Future Plans

A progress report meeting has been tentatively scheduled for March 1, 1972 in Houston. Both Drs. Wulff and Black will attend.

The checks of the global energy balances will be continued.

The optimization program will be expanded to include the identification of system parameters which yield maximum heat loss for a given system volume.

The program ADIABH will be expanded to include the case of "U" shaped tubes. Once this change has been made the program will be inserted into the main program unit.

Respectfully Submitted,

W. Z. Black
Co-Investigator

W. Wulff
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

E-25-609

GEORGIA INSTITUTE OF TECHNOLOGY
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SCHOOL OF
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March 3, 1972

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 26
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems"

Accomplishments

Global Energy Balance checks have been continued. It was found that the treatment of the coolant fluid flow as a quasi-steady process did not alter the results, and that there were two coding errors in the calculation of the volumetric heat capacity and of the check itself. The over-all balance does not yet check completely. Checking is continued.

The radiator system optimization program was executed under the constraint of constant total projected area. The results indicate that the optimum system has short thick fin panels and long coolant tubes; the optimum is not realistic. A meaningful optimum process should involve additonal constraints. Optimization under constant projected area constraint should be performed for fixed, pre-selected fin panel thickness.

Optimization under constant thickness, constant area and under constant system weight has begun, coding of the program modifications are in progress.

The program which calculates the location of the adiabatic plane separating two adjacent flow channels for the case of U shaped tubes has been checked.

Future Plans

Optimization of the fin system will be continued under two different sets of conditions:

(1) Minimum weight
(2) Minimum area with given panel thickness

The program ADIABH and supporting subroutines which call the MRI program for input of sink temperatures will be inserted into the main program unit.

Respectifully Submitted,

W. Z. Black
Co-Investigator

W. Wulff
Co-Investigator

Approved:

S. P. Kezios, Director
School of Mechanical Engineering

WZB:jel

GEORGIA INSTITUTE OF TECHNOLOGY
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SCHOOL OF
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April 14, 1972

Dr. William Simon
Power Generation Branch EP5
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

Subject: Letter Report No. 27
NASA Contract NAS 9-10415
"A Study of the Design Parameters of Space Base and Shuttle Heat Rejection Systems."

Accomplishments

Program changes discussed at the meeting MSC on Monday, March 6, 1972 were carried out as follows:

Input units for mass have been changed to lbm. All other input units are consistent with those listed in Letter Report No. 4. Also the units for input parameters used for the determination of the meteoroid protection thickness will remain in the metric system, since a large majority of the available experimental values are tabulated in the metric system.

The program ADIABH has been checked as a separate program unit. This unit is currently being integrated into the large program.

The original plans for supplying a CALCOMP routine that would plot system results have been dropped due to an incompatibility between the plotting systems of Georgia Tech and NASA. The results to be plotted for purpose of the final report will be completed by hand.

The check of the global energy balances been continued. Several test runs have been completed using various grid sizes. Results from these runs indicate that fluid and fin temperature are rather insensitive to grid size while the unbalance in energy terms is more sensitive to a change in grid size. For example using a typical fin system, a 5 x 5 fin grid size has an unbalance in the energy terms (energy storage, conduction from manifold, enthalpy drop of coolant fluid, net radiant flux) of less than 7%. For the identical system the selection of a 9x9 grid reduces this unbalance to about 1%. The percentage change in the outlet fluid temperature for the same change in grid size, however, is only 0.2%. The changes in the temperature for the interior fin nodes are insignificent.

It is felt that the unbalance can be attributed to the truncation errors involved in attempting to fit a parabola through the interior fin nodes.

This error is particularly significant at the manifold-fin interface were the slope of the temperature profile and the radiant flux is quite steep.

Typing of the rough draft of the final report has been started with approximately 100 pages of text completed. Descriptions of the simplified analysis, the program ADIABH, additional property subroutines and the control deck for mass storage runs are currently being written.

The program logic necessary for accepting variable inlet fluid temperatures and variable inlet mass flow rates has been inserted in the main program. A test case for variable inlet properties is currently being used to check this addition to the program.

The most recent test runs of the large program unit have resulted in a ratio of real time to computation time of approximately 10 to 1.

Future Plans

Work will continue on writing and typing of the final report.

The program ADIABH will be integrated into the main program and checked.

Respectfully submitted,

W. Z. Black
Co-Investigator

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Approved:

S. P. Kezios, Director
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Interim report

GEORGIA INSTITUTE OF TECHNOLOGY

SCHOOL OF MECHANICAL ENGINEERING

ATLANTA, GEORGIA

STUDY OF DESIGN PARAMETERS OF SPACE BASE AND SPACE SHUTTLE HEAT REJECTION SYSTEMS

INITIAL PHASES - I, II and III

Contract No. NAS 9-10415

by

William Z. Black and Wolfgang Wulff

Sponsored by the

Power Generation Branch

Manned Spacecraft Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Houston, Texas

February 1971

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FOREWORD

This report covers the first year phase of a two year research project carried out by the School of Mechanical Engineering at the Georgia Institute of Technology, Atlanta, Georgia for the NASA Manned Spacecraft Center, Houston, Texas, under Contract No. NAS 9-10415. The project title is "Study of Design Parameters of Space Base and Space Shuttle Heat Rejection Systems". The work is monitored by Dr. W. E. Simon of the Power Generation Branch of NASA MSC, Houston, Texas, and was carried out by Dr. W. Z. Black and Dr. W. Wulff as Co-Investigators and Mr. S. M. Morcos and Mr. S. L. Yao, both graduate students, all of the School of Mechanical Engineering under the direction of Dr. S. P. Kezios.

The work carried out by Dr. W. Z. Black is reflected in Part I, Sections A. d and e, and in Part II Chapters 2, 7, 8 and 13. Dr. Black is responsible for the coding of programs No. 14 through 20 and for the supervision of coding programs No. 37 through 46 which was carried out by Mr. Morcos. Dr. Wulff is responsible for the general computer program structure as described in Part I, the analyses in Part II, Chapters 1 and 3 through 6 and 9 through 12, as well as the numerical analysis in Part III, Chapters 14 through 19. Dr. Wulff coded programs No. 1 through 7, 23 through 28 and supervised Mr. Yao in coding programs No. 8 through 13 and No. 29 and supervised Mr. Morcos in coding programs No. 30 through 36 and No. 47 and 48. Dr. Wulff is also responsible for the Simplified Analysis.

The first year program is aimed at the numerical simulation of the Space Radiator System while the second year of the program will be devoted to the system optimization.

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SUMMARY

A transient heat transfer analysis was carried out on a space radiator heat rejection system exposed to an arbitrarily prescribed combination of aerodynamic heating, solar, albedo and planetary irradiation. The radiator system consists of equally spaced parallel coolant flow channels, all in one plane and connected by plane fin panels of trapezoidal cross-section, symmetric with respect to two normal planes, one passing through the tube axis, the other through the center between adjacent tubes. Investigated was one typical tube-fin element and the result extended over the entire system, on the basis of the above symmetry.

The analysis permits to consider both gaseous and liquid coolant fluids, including liquid metals. The flow channels are covered with a meteoroid protection layer whose thickness is predicted. The entire radiator system is covered with the same passive thermal control coating with optically diffuse but wavelength and temperature dependent optical properties.

The major results of the analysis are the prediction of both transient and steady-state, two-dimensional temperature profiles, the local and total heat rejection rates, and the coolant flow pressure drop in the flow channel, and of the total system weight and the protection layer thickness.

A computer program consisting of 48 program units was coded to execute the numerical solution of the system of differential equations occurring in the analysis and to predict principal design paramters. The modular program structure permits readily later modifications.

A simplified analysis was carried out to aid the detailed analysis as well as the optimizations planned for the second program phase. This analysis led to a small computer program. Regarding the heat rejection rates, its results are, for two test cases carried out so far, within 4% in agreement with the results of the detailed analysis.

The analysis developed so far will be an integral part of the radiator system optimization planned for the second year program phase.

This report is written in three parts. The user of the computer code needs to concern himself only with Part I, titled Operation Manual. The analysis and the governing equations are contained in Part II, titled Analysis. The numerical techniques are covered in Part III. Details which the reader intending to expand the program may need are placed into the appendices where one can also find the simplified analysis.

I. OPERATIONAL MANUAL

This chapter familiarizes the user of the computer code developed during the first year program phase, with the deck composition, the data input formats, the running mode options and the output formats.

The program consists of 48 program units and the Data Set. The source language is FØRTRAN V. The program was executed, via temporary files, through batch processing on the UNIVAC 1108 computer operating under EXEC 8, Version 26.70.36:C4, at the Georgia Tech RECC Data Processing Center.

Executive Control Statements are not discussed as they may be freely chosen by the user in accordance with the Executive Control Language. All statements are in 026 key punch code.

Changes in both the program structure, the running options and the execution modes are expected to arise during the second year program phase. The program as presently written serves to simulate the radiator system performance. Even though successive runs with system parameter variations are feasible at present, there is no provision for systematic system optimizations.

A. The Deck Assembly

The program structure is dictated by the calling sequence of the Runge-Kutta-Simpson integration procedure (see Section III-15). The Source Deck consists of two parts. The first part, referred to as the Permanent Part, requires no attention from the user unless he plans major program modifications, for instance to accommodate geometrical configurations other than the one considered here. The Permanent Part contains the first 29 program units.

The second part, called the Selective Part, is assembled from case to case by the user in accordance with his choice of the

(i) coolant fluid

(ii) flow channel material

(iii) meteoroid protection layer material

(iv) fin panel material

(v) thermal control coating

There are always 19 program units in the Selective Part.

Following the Source Deck is the Data Set which will be discussed in Chapter I-B and consists of four groups one for each of the following input specifications:

(i) ascent and reentry profiles

(ii) solar, albedo and planetary irradiation

(iii) system specifications

(iv) program options.

Most of the user's activities will be reflected in his manipulation of the Data Set, especially of the data in groups (iii) and (iv) above.

The Permanent Part contains 29 program units grouped in seven sets from (a) through (g) as follows:

a) the principal integration program set with

1. MAIN, the main program unit which

provides	α)	input and output
	β)	unit conversion
	γ)	computation of design parameters
	δ)	preparations for principal integration,
calls	α)	RKS, DERIVM, CNTLM, for principal integration
	β)	FLSTRT to establish the initial flow field
	γ)	FUNCTIØN subprograms for fluid and structural material properties
	δ)	QINCID, SHAPEF (see group c)
	ε)	mathematial procedure subprograms,

2. SUBRØUTINE DERIVM (Y,DY,TIME) which is called from RKS,

receives	α)	the current system state variables Y
	β)	the current time TIME,
provides	α)	all derivatives of the variables Y with respect to time,
calls	α)	CØNVEC, QRAD
	β)	FLSTRT to establish the flow field
	γ)	FUNCTIØN subprograms for fluid and structural material properties
	δ)	mathematical procedure subprograms,

3. SUBRØUTINE CNTLM (Y,DY,DX,X,NTRY,IFVD) which

is called from RKS,

receives α) all system state variables Y

β) their derivatives DY

γ) current time X, step size DX,

provides α) output during integration

β) integration step size control

γ) integration termination criteria,

calls α) HFL, fluid enthalpy subprogram

β) mathematical procedure subprograms,

b) the secondary integration program set, necessary to establish the dynamic fluid flow field, with

4. SUBRØUTINE FLSTRT (RE,PR,DELTA) which

is called from MAIN, DERIVM

receives α) RE, the mean Reynolds number

β) PR, the mean Prandtl number

γ) DELTA, the diameter-to-length ratio for the tube,

provides α) fluid flow (inital and current) conditions

β) table heading for initial conditions,

calls α) TRNSPT to compute friction factor and convective film coefficient (in non-dimensional form)

β) RKSF, DERIVL, CNTLN

γ) fluid flow property subprograms

δ) mathematical procedure subprograms

5. SUBRØUTINE DERIVL (Y,DY,X) which

is called from RKSF,

receives α) local fluid flow variables Y

β) position along flow channel axis, X,

provides α) spatial derivatives DY of Y,

6. SUBRØUTINE CNTLN (Y,DY,DX,X,NTRY,IFVD) which

is called from RKSF,

receives α) the flow variables Y

β) their spatial derivatives DY

γ) position X, interval DX along channel axis,

provides α) output when initial conditions are established

β) termination criteria for RKSF integration,

7. SUBRØUTINE TRNSPT (RE,PRL,DELTA,FR,FNU) which computes non-dimensional friction factor and convective film coefficient, Eqs. 3.7 through 9 and Eqs. 3.16 through 18, and

is called from FLSTRT,

receives α) Reynolds number RE

β) Prandtl number PRL

γ) diameter-to-length ratio DELTA,

provides α) FR = $4f/\delta$, Eq. 3.32

β) FNU = $4\ N_{Nu}/(\delta\ N_{Re}\ N_{Pr})$, Eq. 3.37

c) The program set used to calculate the incident net radiant flux, with,

8. SUBRØUTINE QINCID which

   is called from MAIN,

   provides α) data transfer from the SRI Incident Radiation Computer program

   β) averaging of radiant flux over circumference of tube cross-section,

9. SUBRØUTINE SHAPEF which

   is called from MAIN,

   provides exchange function SS as defined by Eq. 6.15, see Appendix D.,

10. SUBRØUTINE TRMATX which

   is called from QRAD,

   provides the evaluation of the transfer matrix M_{ij}, defined by Eq. 6.7,

11. SUBRØUTINE EXITAV which

   is called from QRAD,

   provides the evaluation of the exitation vector P_j in Eq. 6.18,

12. SUBRØUTINE ABSØRB which

   is called from QRAD,

   receives α) total hemispherical emittance ε, see Eq. 6.5

   β) temperature distributions on the fin and tube surfaces

   γ) exchange function SS

   δ) functions x_{ij} and x_{ijk} defined by Eqs. 6.10 and 6.11, provides absorptance matrix α_{ij} as defined by Eq. 6.9

calls
α) SHAPEF for SS

β) EMIT for (T)

γ) AVGEMT for x_{ij} and x_{ijk}

δ) DEFINT for integration,

13. SUBRØUTINE QRAD which

is called from DERIVM ,

receives α) transfer matrix and exitation vector M_{ij} and P_j , respectively,

provides
α) inversion of transfer matrix

β) solution of radiosity equations

γ) grid mapping,

calls
α) TRMATX

β) EXITAV

γ) YINT, INTERP,

e) the program set used to calculate the aerodynamic heating during ascent and reentry, consisting of

14. FUNCTIØN ALTSH (TIME, IØPTN, ALTA, ALTR, TA, TR, NA, NR) which interpolates user-supplied altitude profiles for a given instant, and

is called from CØNVEC,

receives α) current real time, TIME, in seconds, measured from start of transition phase, i.e. ascent: TIME = 0, ALTSH = ALTA (1)
reentry: TIME = 0, ALTSH = ALTR (1)

β) ordered pairs of time and altitude (TA,ALTA) and (TR,ALTR) for ascent and reentry, respectively

γ) NA and NR, the number of ordered pairs and elements in TA,ALTA and TR,ALTR, respectively,

δ) IØPTN = 0 for ascent
1 for reentry,

provides data interpolation,

calls YINT for interpolation,

15. <u>FUNCTIØN VELSH</u> (TIME, IØPTN, VELA, VELR, TA, TR, NA, NR) which interpolates user-supplied velocity profiles for any time during shuttle service, and

is called from CØNVEC,

receives the same data as program unit No. 14 except that ALTA and ALTR are replaced by the velocities VELA and VELR for ascent and reentry, respectively,

provides data interpolation,

16. <u>SUBRØUTINE ATMØS</u> (ELEV, TPE, CP, TATM, CATM) which computes the atmospheric temperature and the speed of sound as functions of altitude and

is called from CØNVEC,

receives α) current shuttle elevation, ELEV, in feet

β) ordered pairs of atmospheric temperature (TPE) and specific heat at constant prresure (CP), provides atmospheric temperature, TATM in degrees R and speed of sound, CATM, in ft/sec,

calls YINT for interpolation, PØLY for evaluation of polynomials

17. SUBRØUTINE REFP (ELEV,TPE,CP,REFTP,REFPR,REFVIS,REFRHØ,REFK, REFCP,REFGAM) which computes the atmospheric air properties as a function of elevation and of high speed reference temperature and

is called from CØNVEC,

receives

α) current orbiter elevation, ELEV, in feet

β) ordered pairs of atmospheric temperature TPE in degrees R and specific heat at constant pressure CP in Btu/(lbm R)

γ) current high speed reference temperature REFTP, in degrees R,

provides atmospheric Prandtl number REFPR (dimensionless), dynamic viscosity REFVIS in lbm/(ft sec), density REFRHØ in lbm/ft^3, thermal conductivity REFK in Btu/(sec ft R), specific heat at constant pressure REFCP in Btu/(lbm/R) and the ratio of specific heats REFGAM (dimensionless).

calls YINT for interpolation

PØLY for polynomial expansion,

18. SUBRØUTINE NUS (MACHNØ,TATM,CATM,ITN,PRATM,VISATM,RHØATM,STAGX, VERTX,NSRAD,NUS1) which provides a single Nusselt number for the calculation of the aerodynamic heating of the orbiter radiator system at the current time and

is called from CØNVEC

receives

α) current orbiter Mach number MACHNØ (dimensionless)

β) current atmospheric temperature TATM, in degrees R

γ) current atmospheric velocity of sound, CATM, in ft/sec

ε) temperature of the coolant fluid at the inlet plane TIN, in degrees R

ζ) atmospheric Prandtl number PRATM, evaluated at the high speed reference temperature (dimensionless)

η) atmospheric density RHØATM, evaluated at the high speed reference temperature in lbm/ft

θ) distance from the stagnation point on the shuttle vehicle to the midpoint of the radiator panel measured along a streamline, STAGX, in feet

ι) overall dimension of the radiator panel measure in a direction parallel to the acceleration of gravity, VERTX, in feet

κ) integer value indicating number of non-adiabatic sides of the radiator panel, NSRAD i.e. NSRAD = 1 for single non-adiabatic surface or NSRAD = 2 for both sides of radiator being non-adiabatic,

provides

mean Nusselt number NUS1, for meteoroid layer and fin at current orbiter elevation during either ascent or reentry (dimensionless),

calls

YINT for interpolation,

19. SUBROUTINE CØNVEC (TIME) which computes normalized aerodynamic heating of fin and meteoroid protection layer for both ascent and reentry phases the of orbiter operation and

is called from DRIVM,

receives α) current real time TIME, in seconds, measured from start of transition phase; i.e. TIME must be measured with respect to same reference point as user supplied time arrays in FUNCTIØN ALTSH and VELSH,

provides normalized convective flux from fin surface CØNFN (I,J), and from meteoroid protection surface CØNMP(I),

calls α) ALTSH for altitude of orbiter

β) VELSH for velocity of orbiter

γ) ATMØS for atmospheric properties

δ) REFP for atmospheric properties evaluated at high speed reference temperature

ε) YINT for interpolation

ζ) NUS for Nusselt number,

f) the program to compute the thickness of the meteoroid protection layer

20. FUNCTIØN TK (GAMMA,A,BETA,DENSM,THETA,PHI,AN,ALPHA,VELM,PØ, TAU,DENSTY,W,TNN,AMAN,TIN,RØUT) which computes the thickness for given environmental conditions, tube and manifold areas, experimental constants and protection layer properties and

is called from MAIN,

receives α) nondimensional experimental constant, GAMMA, see Eq. 8.9

β) nondimensional experimental constant A, see Eq. 8.9

γ) nondimensional constant which relates meteoroid flux to mass, BETA

δ) density of the metoroid particle, DENSM, in gm/cm ε) nondimensional experimental constant THETA, see Eq. 8.9

ζ) nondimensional experimental constant PHI, see Eq. 8.9

η) nondimensional constant AN, used to describe penetration depth as a function of angle of incidence of meteoroid particle

θ) velocity of meteoroid particle relative to radiator panel, VELM, in ft/sec

ι) probability of no damage caused by impact of meteoroid, PØ

κ) time TAU, the radiator panel is exposed to meteoroid environment, in days

λ) density of protection material DENST, in lbm/ft

μ) axial length of single flow channel exposed to meteoroid envirionment, W, in inches

ν) integer number of flow channels, TNN,

ξ) area of the manifold that is exposed, AMAN, in ft

φ) temperature of coolant fluid at inlet plane of flow channel, TIN, in degrees R

π) outside radius RØUT of the unprotected flow channel, in inches,

provides — meteroid protection thickness TK, in inches,

calls — ELAS for modulus of elasticity of protection material,

g) the program set consisting of all the mathematical procedures discussed in detail in Chapter III:

21. SUBRØUTINE RKSF (see Sect. III.15) which

    is called from   FLSTRT, for dynamic fluid flow field,

    calls   DERIVL,CNTLN,

22. SUBRØUTINE RKS (see Sect. III.15) which

    is called from   MAIN, for principal integration,

    calls   DERIVM,CNTLM

23. FUNCTIØN PØLY (X,A,M) (see Sect. III.16),

24. FUNCTIØN YINT (X,Y,M,N,P) (see Sect. III.17),

25. SUBRØUTINE DDX (Y,DY,DX,N)
26. SUBRØUTINE D2DX2 (Y,D2Y,DX,N) } (see Sect. III.18)

27. FUNCTIØN DEFINT (Y,DX,N)
28. SUBRØUTINE FINT (Y,YO,DX,N,F) } (see Sect. III.19),

29. SUBRØUTINE INTERP (NX1,MZ1,XX1,ZZ1,YY1,NX2,MZ2,XX2,ZZ2,YY2)maps a two-dimensional function YY1 from one grid(XX1,ZZ1) onto another grid (XX2,ZZ2) and

    is called from   QRAD,

    receives   α) the number of nodal points (NX1,MZ1) of the original grid

                          β) the function YY1

                          γ) the number of nodal points (NX2,MZ2) of new grid,

    provides   the function YY2 at the new grid,

    calls   YINT,

    is restricted to   NX1,MZ1,NX2,MZ2 $\leq$ 10

The Selective Part contains five groups of thermophysical properties, with the total of 19 program units. Each group constitutes a property package, one each for

(i) the coolant fluid (7 program units)

(ii) the flow channel material (3 program units)

(iii) the meteoroid protection layer (4 program units)

(iv) the fin material (3 program units)

(v) the thermal control coating (2 program units)

The choice of a particular material combination must be reflected in the corresponding data specification of the Input Data Set, (see Sect. c of Chap. B).

a) The coolant property subprogram set consists of

30. FUNCTIØN RHØF (P,T) which computes the fluid density RHØF in slug/ft^3 as a function of pressure P in lb /ft^2, and absolute temperature T in R,

31. FUNCTIØN BETA (RHØ,T) which computes the isoborric expansion coefficient β , Sect. II.C.11, in 1/R as a function of density RHØ in slug/ft^3, and temperature T in R,

32. FUNCTIØN CAPPA (P,T) which computes the isothermal compressibility, Eq. 11.3, in ft^2/lbf, as a function of pressure P in lbf/ft^2, and temperature T in R,

33. FUNCTIØN CPF (RHØT) which computes the specific heat at constant pressure CPF, in Btu/(slug R), as a function of density RHØ in slug/ft^3, and temperature T, in R,

34. FUNCTIØN HFL (RHØ,T) which computes the fluid enthalpy HFL, in Btu/slug, as a function of density RHØ in slug/ft^3, and temperature T, in R,

35. FUNCTIØN VISC (RHØ,T) which computes the fluid dynamic viscosity VISC, in slug/(ft sec) as a function of density RHØ in slug/ft^3, and temperature T, in R,

36. FUNCTIØN THCF (RHØ,T) which computes the fluid thermal conductivity THCF in Btu/(hr ft R) as a function of density RHØ in slug/ft^3, and temperature T, in R,

For specific details see Sect. II.11 and 12 and Appedix B.

b) The coolant channel material property subprogram set consists of three elements, 37 through 39:

37. FUNCTIØN THCTB (T) computes the thermal conductivity THCTB in Btu/(hr ft R), of the tube wall material as a function of the absolute temperature T, in R,

38. FUNCTIØN DTHCTB (T) computes the relative change of thermal conductivity k with temperature T, namely $(dk_w/dT)/k_w$ in 1/R, as a function of temperature T, in R,

39. FUNCTIØN CPTB (T) computes the specific heat at constant pressure CPTB, in Btu/(slug R) as a function of T, in R.

For specific details of property representation see Appendix A.

c) The meteroid protection layer material properties are coded in a set of four elements, 40 through 43:

40. FUNCTIØN THCMP (T)
41. FUNCTIØN DTHCMP (T)
42. FUNCTIØN CPTB (T)

same purpose for protection layer as for channel wall. (see 36, 37 and 38 respectively)

43. FUNCTIØN ELAS (T) computes the modulus of elasticity ELAS in lbf/in^2 as a function of temperature T, in R.

d) The fin material properties required are coded in three FUNTIØN subprograms, numbered 44 through 46:

44. FUNCTIØN THCFN (T) computes the thermal conductivity THCFN, in Btu/(hr ft R) for the fin material as a function of absolute temperature T, in R,

45. FUNCTIØN DTHCFN (T) computes the relative change of thermal conductivity, namely $(dk_f/dT)/k_f$ in 1/R, as a function of temperature T, in R,

46. FUNCTIØN CPFN (T) computes the specific heat at constant pressure CPFN, in Btu/(slug R) as a function of temperature T, in R.

e) Optical properties of the thermal control coating are coded in two subprograms, numbered 47 and 48.

47. FUNCTIØN EMIT (T) computes the total hemispherical emittance in accordance with Eq. 6.5 as a function of the surface temperature T in R, and is called by ABSØRB and EXITAV,

48. SUBRØUTINE AVGEMIT (T,XX,XXX,N) evaluates the expressions for x_{ij} and x_{ijk} given as Eqs. 6.10 and 11 for N interacting surface elements. It is called by ABSØRB (see program No. 12).

This completes the Source Deck discussion. Recall that the Source Deck composition implies a particular selection of coolant fluid and structural materials.

B. The Input Data Set

Input data are divided in four groups and assembled in the order of increasing frequency of changes so that data records most likely to be changed are at the end of the Data Set. This enables the user to keep large portions of the Job Deck on mass storage. The four groups in the Data Set define

(i) the ascent and reentry profiles

(ii) the incident thermal radiant flux as a function of time

(iii) the system specifications, other than material selections

(iv) the options of program execution.

Item (ii) may be eliminated during the second contract phase provided a contractor-supplied computer program can be arranged to transfer its results internally (after simultaneous execution).

The program may be executed successively after reading new data records beginning either at the first record of group (i), or at the first record of group (ii) or at any variable in groups (iii) and (iv). When data are reread from group (i) then data in groups (ii) or (iii) or (iv) may be skipped; the same holds true for reentering the Data Set from any other group.

None of the data groups contains a fixed number of records. The number of records in groups (i) and (ii) are determined and specified to the computer by the user. Groups (iii) and (iv) contain a minimum of records as specified below; the number of additional records in this group and of additional sets of groups (i) and (ii) depends on the number of additional executions and parameter variations during the same job. In the description of data records (card images) the numbering starts from one in each group.

a) Ascent and Reentry Data

Card No.	FØRMAT	Variable
1	2I10	NA,NR the number of ordered pairs of elements in the velocity-time and altitude-time arrays for ascent and reentry profiles, respectively
2 INT*(NA/10+0.9) + 1 = N_1	10F8.3	TA, elements of time array (NA values) in seconds, selected for ascent velocity and elevation profiles
N + 1 through N+INT(NR/10+0.9) = N_2	10F8.3	TR, elements of time array (NR values) in seconds, selected for reentry velocity and elevation profiles
N +1 through N +INT(NA/8+0.875) = N_3	8E10.3	VELA , elements of velocity array (NA values) in ft/sec, selected for ascent velocity profile of orbiter
N +1 through N +INT(NR/8+0.875) = N_4	8E10.3	VELR, elements of velocity array (NR values) in ft/sec, selected for reentry velocity profile of orbiter
N + 1 through N +INT(NA/8+0.875) = N_5	8E10.3	ALTA, elements of altitude array (NA values) in ft, selected for ascent elevation profile of orbiter
N + 1 through N +INT(NR/8+0.875)	8E10.3	ALTR, elements of altitude array (NR values) in ft, selected for reentry elevation profile of orbiter

* INT(x) = Integer part of x

b) <u>Irradiation Data</u>

This data set is temporary; it follows the last card of the data described in (a) above.

Card No.	FØRMAT	Variable
1	2I3	NTM, NSRAD (i) number of instances at which incident fluxes are to be specified, NTM < 100 (ii) NSRAD = 1 one panel is exposed NSRAD = 2 both panel sides are exposed;
2 through NTM+1	10F8.3	on each card: (i) time TM (in seconds) (ii) 3 values of solar (iii) 3 values of albedo irridiation (iv) 3 values of planetary Btu/hr ft) incident at TM and each coming from one of three directions, in this order: (i) $-30°$ (ii) $0°$ from the panel normal (iii) $+30°$ (upper side)
NTM+2 through 2*NTM+1	10F8.3	same data as above, now for lower fin panel side, only if NSRAD = 2

c) System Specifications

The system specifications define the radiator system and follow immediately after the ascent and reentry profile definitions.

The first four cards in the group of the system specification data contain the names of

(i) the tube material

(ii) the fin material

(iii) the coolant fluid

(iv) the meteoroid protection layer material

in alphanumeric form, beginning with an alphabetic character. Each name is punched on a separate card, beginning in the first column and extending no further than through the first twelve columns. These names serve to identify the printout of results. The user must supply these names in agreement with the composition of the Selective Part described in Chapter I.A. The subsequent data records contain numerical data.

Numerical system specifications are read into the computer in NAMELIST format, one NAMELIST each with name and input data as follows:

TUBE for flow channel specifications,

FLØW for coolant fluid flow specifications,

FIN for fin parameter specifications,

PRØTLR for the protection layer specifications,

MANIFD for the manifold input data.

Each input data record under NAMELIST format has

(i) a blank in its first column,

(ii) a $ - sign in its second column,

(iii) the NAMELIST name, starting in the third column, followed by one or more blanks,

(iv) the string of data in free field format as follows:

A = b,

where (A) is the variable name and (b) is a number; imbedded blanks between (A),(=),(b),(,) and a following (A) are permissible,

(v) the comma of the last datum is to be placed by a \$ - sign which delimits the NAMELIST data string.

For more details concerning NAMELIST formating, the reader may consult standard texts on FØRTRAN PROGRAMMING. The NAMELIST data strings must be sequenced in the order in which they are listed here:

(i) NAMELIST/TUBE/ contains 7 variables:

DITBI	internal (hydraulic) tube diameter in inch,
STBI	tube wall thickness, in inch,
XL	tube length, in ft,
RHØTB	tube wall density, in slug/ft^2,
MZ	number of nodal points along the tube axis (no. of intervals plus one), $\leq$ 10,
NRTB	number of nodal points in radial direction , in the tube wall, $\leq$ 5,
NTBS	number of flow channels.

(ii) NAMELIST/FLOW/ contains 8 variables:

MDØTI	total coolant mass flow rate, in lbm/hr,
TO	entrance (and reference) temperature in degrees R,
PO	entrance (and reference) pressure in lbf/ft .

(iii) NAMELIST/FIN/ contains 5 variables:

NX	number of nodal points on the fin, perpendicular to the channel axis, NX $\leq$ 10,
SRØØTI	fin root thickness, in inch,
HFNI	fin height, from root to tip, in inch,
STIPI	fin tip thickness, in inch,
RHØFN	fin material density, in slug/ft.

(iv) NAMELIST/PRØTLR/ contains 13 variables:

NRMP	number of radial nodal points in the protection layer, $\leq$ 5,
RHØMP	protection layer material density, in slug/ft^3,
RHØMET	meteoroid density in g/cm
VELM	meteoroid velocity in ft/sec,
TAU	time that vulnerable area is exposed to meteoroid environment, in days,
PRØB	probability of no damage caused by meteoroid impacts, dimensionlesss,
ALPHA	experimental constant that relates meteoroid flux and mass (See Eq. 8.4) in gm/(day ft^2),
BTA	experimental constant that relates meteoroid flux and mass (See Eq. 8.4) dimensionless,
GAMMA	empirical constant used to adjust predicted penetration depths to ones observed experimentally (See Eq. 8.1) dimensionless,
PHI	empirical constant (see Eq. 8.1) dimensionless,

THETA empirical constant (see Eq. 8.1) dimensionless,

ATK empirical constant used to account for spalling on a target of finite thickness (see Eq. 8.8) dimensionless,

AN experimental constant that describes penetration depth as a function of angle of incidence (see Eq. 8.6) dimensionless

(v) NAMELIST/MANIFD/ contains

AMAN total mainfold area, projected into the fin plane, in ft^2.

Any one of these variables may be changed for successive program executions by entering them in NAMELIST/GINPT/ as discussed below.

d) Execution Control Options

The user has the choice of options for the execution of the first as well as successive computer runs. These options are likely to increase in the second contract phase.

Two data records are considered to be execution controls: RUNØPF and GINPT.

(vi) NAMELIST/RUNØPT/ contains 8 variables:

MSTØTR = 1 to compute steady state conditions

= 2 to simulate transient system performance

DTWRTE fixed time interval, in hr, between data printout during integration

TEND termination time, in hr, for transient performance calculation

ALIMIT absolute error limit per integration step, see Eq. 15.3

RLIMIT		relative error limit per integration step, see Eq. 15.3
TI		initial temperature, in degrees R
LIMWRT		maximum number of data recording during integration toward steady state, exclusive of initial conditions record and steady state record.
NCØNV	= 0	no aerodynamic heating
	= 1	ascent
	= 2	reentry

(vii) NAMELIST/GINPT/ contains every variable name listed in items (i) through (vi). If this record is omitted, the program will terminate. If this NAMELIST is encountered with any or all variables the execution is restarted with

new system specifications and/or

new run option controls and

old ascent and reentry profiles and

old irradiation profiles.

There may be as many NAMELIST/GINPT/ records as computing time permits.

C. Computer Output

The first output record consists of a list of all system specifications and execution control data as listed in Section c of Chapter I.B, items (i) through (vi), all in NAMELIST format (see Fig. 1).

Next, there are listed the initial coolant fluid flow properties in nondimensional form, together with their respective reference quantities. Table headings and variable identifications are self-explanatory (see Fig. 2).

The initial line conditions are followed by a list of system parameters which can be computed prior to the integration of the governing differential equations. These parameters (see Fig. 2) include material specifications, important dimensions, weights and the total area.

Following the above preliminary results is a series of current system descriptions printed during the integration process (see Fig. 3). These descriptions include the current time, the fin panel temperature distribution, the local heat rejection rates and the total radiant and aerodynamic heat rejection rates. Furthermore, a second table lists the coolant fluid flow properties as functions of axial distance as well as the local cooling rate. All properties are tabulated in nondimensional form; every table is preceeded by a list of necessary reference quantities.

Specified in the second table, below the reference quantities, are the inlet -, the exit - and the total change in stagnation enthalpy fluxes; they are labelled, respectively, HI, HE and DH. Also, for comparison, there is listed the enthalpy flux at reference state (T_o,p_o) and reference velocity w_o.

The last table of current output data constitutes either the system conditions at the specified termination time, TEND in hr, or the steady-state condition, depending on whether MSTØTR = 1 or MSTØTR = 2, respectively.

The results of two full-scale computer results are compared below with the corresponding results obtained by the simplified analysis which is discussed in Appendix D. The first of the results listed below corresponds to the case for which the complete output records are reproduced as Figures 1 through 3.

Case	Φ	N_c	η	N_{Re}	Heat Rejection Btu/hr full scale	simplified	Rel. Error %
1	0.05763	0.0134	0.9822	158.7	1.1679×10^5	1.159×10^5	0.7
2	0.05763	0.0544	0.9337	158.7	1.1689×10^5	1.126×10^5	3.7

TABLE 1 Comparison of Full-Scale and Simplified Analyses

```
6XOT
 $TUBE
 DITBI    =     .25000000E+00
 STBI     =     .10000000E+00
 XL       =     .15000000E+02
 RHOTB    =     .52599999E+01
 MZ       =                +5
 NKTBI    =                +3
 NTBS     =               +12

 $END
 $FLOW
 MDOTI    =     .60000000E+03
 TO       =     .50000000E+03
 PO       =     .25000000E+04

 $END
 $FIN
 NX       =                +5
 SROUTI   =     .50000000E-01
 HFNI     =     .40000000E+01
 STIPI    =     .50000000E-01
 RHOFN    =     .52599999E+01
 STAGX    =     .20000000E+02
 VERTX    =     .10000000E+02
 NSRAD    =                +2

 $END
 $FROTLR
 NRMP     =                +3
 RHOMP    =     .35500000E+01
 RHOMET   =     .25800000E+00
 VELM     =     .65600000E+05
 TAU      =     .36500000E+04
 PROB     =     .98999999E+00
 ALPHA    =     .18800000E-09
 BTA      =     .12130000E+01
 GAMMA    =     .15000000E+01
 PHI      =     .50000000E+00
 THETA    =     .66666700E+00
 ATK      =     .17500000E+01
 AN       =     .10000000E+01

 $END
 $MANIFD
 AMAN     =     .43000000E+02

 $END
 $RUNOPT
 MSTOTR   =                +2
 DTWRTE   =     .99999999E-02
 TEND     =     .33333000E-01
 ALIMIT   =     .50000000E-04
 RLIMIT   =     .10000000E-04
 T1       =     .40000000E+03
 LIMKRT   =                +3
 NCONV    =                +1

 IOPTN    =                +0

 $END
```

Figure 1. Record of System Specifications and Execution Control Data

PT.NO.	POSITION Z	PRESSURE P	VELOCITY W	FLUID TEMPERATURE T	WALL TEMPERATURE TWI
1	.000	1.000000	.937067	.800000	.800000
2	.250	.987382	.937095	.800002	.800000
3	.500	.974763	.937122	.800004	.800000
4	.750	.962144	.937149	.800006	.800000
5	1.000	.949525	.937176	.800007	.800000

```
INLET PRESSURE    PO  =   2500.000  LBF/SQ.FT
REF.  VELOCITY    WO  =     .73055  FT/SEC
REF. TEMPERATURE TOO  =    500.000  R

      REYNOLDS NO     =             .15829+03
      PRANDTL  NO     =            94.083629
      DELTA           =              .001389
      REL.PRESSURE IS               .135116+04

INIT. NUSSELT NO. NU  =             .468158+01
WALL BIOT NO.     BI  =             .221421-02

        SYSTEM PARAMETERS
        *****************

NUMBER OF TUBES ,              NTBS =        12
TUBE LENGTH ,                    XL =    15.000 FT
     INTERNAL DIAMETER ,       DITB =      .250 IN
     WALL THICKNESS ,           STB =      .100 IN
     MATERIAL                           ALUMINUM
     MASS    (ALL TUBES) ,      MTB =     .7202 SLUG

FIN HEIGHT ,                    HFN =     4.000 IN
     THICKNESS AT ROOT ,      SROOT =      .050 IN
     THICKNESS AT TIP ,        STIP =      .050 IN
     MATERIAL                           ALUMINUM
     MASS (ALL FINS) ,          MFN =    2.6200 SLUG

COOLANT FLUID IS                        SILICONE OIL
     MASS (IN ALL TUBES) ,      MFL =    1.3620 SLUG

PROTECTION LAYER THICKNESS,     SMP =      .063 IN
     MASS,                      MMP =      .349 SLUG
     MATERIAL IS                        BERYLLIUM

TOTAL MASS (EXCL. MANIFLD.)    MTOT =    5.0517 SLUG
TOTAL AREA (SINGLE NORMAL PROJECTION) ,
                               ATOT =  126.7500 SQ FT
```

Figure 2. Initial Coolant Flow Conditions and System Design Parameters

RELATIVE TIME IS 120.8109

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 500.000 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .8570+03 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1294+05 BTU/HR , AERODYN. HEATING POWER, QCONV = .0000 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	1.6029	.9226	.9226	.9226	.9225	.9225
.250	1.0167	.8360	.8267	.8201	.8162	.8149
.500	.9433	.8200	.8112	.8050	.8013	.8001
.750	.8618	.8008	.7929	.7873	.7839	.7828
1.000 (EXIT)	1.0769	.8353	.8353	.8353	.8353	.8353

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 500.000 R
REFERENCE PRESSURE, P00 = 2500.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .731 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .867533+04 BTU/HR
EXIT CURRENTLY EI = -.391338+04 BTU/HR

INLET CURRENTLY HI = .867551+04 BTU/HR
TOT. REJECTION DH = .116889+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9226	.9226	42.723417	.00000
.250	.98656	.9901	.9660	.8360	.8360	71.745527	.25084
.500	.97325	.9813	.9423	.8200	.8200	67.445761	.54166
.750	.96004	.9733	.9112	.8008	.8008	60.915485	.79972
1.000 (EXIT)	.94692	.9666	.8922	.8353	.8353	31.430184	1.00000

Figure 3. Typical Record of Current System Variables

II ANALYSIS

The analysis is presented in three major parts. In the first part are developed the governing equations of transient heat transfer within and from the radiator system; these equations are the basis of the numerical simulation. The second part of the analysis is devoted to the computation of design parameters dictated by operational conditions, while in the third part there is covered the development of thermodynamic and transport properties of structural materials, coolant fluids, and the atmosphere.

NOMENCLATURE

a	empirical constant used to account for spalling of protection layer (Eq. 8.8)	
a	function of temperature, used to express the isothermal compressibility and the zero-pressure isobaric thermal expansion coefficient, see also b and c (Eq. 11.9)	
a_z	axial fluid flow acceleration	ft/sec
A	area	ft^2
A_n	coefficients in polynomial for atmospheric pressure at high altitudes (Eq. 13.8)	-
A_s	surface area	ft^2
A_x	cross-sectional area perpendicular to x coordinate	ft^2
A_z	cross-sectional area perpendicular to z coordinate	ft^2
b	defined in Eq. 11.9, see also a	
B	fin geometrical parameter (Eq. 2.14)	-
B_N	coefficients in polynomical for atmospheric density at high altitudes (Eq. 13.9)	-
c	atmospheric speed of sound	ft/sec
c	negative slope of fin sides	-
c	defined in Eq. 11.9, see also a	
c	speed of light	ft/sec
$\bar{c}$	speed of sound in meteoroid protection material	ft/sec
c_p	specific heat at constant pressure	Btu/(slug R)
c_v	specific heat at constant volume	Btu/(slug R)

c_v	zero-pressure specific heat at constant volume	Btu/(slug R)
d	diameter of meteoroid particle	in
d	tube diameter	ft
D	fin geometrical parameter (Eq. 2.15)	-
E	emissive power	Btu/(hr ft^2)
E	modulus of elasticity	lbf/in^2
E	relative error	-
f	Fanning friction factor	-
F	cumulative meteoroid flux (eq. 8.4)	1/(ft^2 day)
F	dimensionless parameter, Eqs. 3.31-34	
g_c	32.174 ft lbm/(lbf sec^2)	
h	Plank's constant, $h = 6.625 \times 10^{-34}$ W s^2	
h	specific enthalpy	Btu/slug
H	geopotential altitude	ft
H	fin height, from root to tip	ft
h_c	convective film coefficient	Btu/(hr ft^2R)
h_i	convective heat transfer coefficient used in reference enthalpy method	lbm/(hr ft^2)
k	Boltzmann constant, $k = 1.380 \times 10^{-23}$ Ws/K	
k	thermal conductivity	Btu/(hr ft R)
L	temperature gradient in atmosphere (Table 5)	(K/km)
L	tube (and fin) length	ft
M	Mach number of orbiter	-
M	mass	slug
M	molecular weight	-
M_{ij}	transfer matrix Eq. 6.19	

M_m	inverted M	-
M	defined by Eq. 10.22	
n	constant that describes depth of penetration as a function of angle of incidence (Eq. 8.6)	-
n	number of tubes	
n	refractive index	-
N	cumulative number of meteoroid impacts	-
N_{Bi}	Biot number	-
N_{Fo}	Fourier number	-
N_{Gr}	Grashof number	-
N_{Nc}	Conductance parameter	-
N_{Nu}	Nusselt number	-
N_{Re}	Reynolds number	-
N_{Pr}	Prandtl number	-
p	absolute pressure	lbf/ft^2
p_j	nondimensional exitation vector, Eq. 6.21	-
P_j	exitation vector, Eq. 6.18	
P_o	probability of no damage due to meteoroid impact	-
P_∞	depth of penetration of a meteoroid particle into an inifinite target	in
q''	heat flux	$Btu/(hr\ ft^2)$
$\tilde{q}$	nondimensional heat flux	-
$\bar{Q}_o$	nondimensional inlet power flux	-
$\bar{Q}_{rad}$	defined by Eq. 10.21	-
r,z	polar coordinates, see Fig. 4	ft
r	recovery factor	-

R^*	universal gas constant	ft lbf/(lb mole R)
R	outer meteoroid protection layer radius	ft
s	thickness	ft
$s_f = \frac{s_r}{2}$	fin half thickness at root	ft
$\bar{s}_f$	normalized fin thickness (Eq. 2.13)	-
$\overline{s_i s_j}$	direct exchange area (Eq. 6.1)	ft^2
S	constant in atmospheric viscosity equation (Eq. 3.7)	K
SS	direct exchange "area", partially evaluated	ft
t	time	hr
T	absolute temperature	R
u	specific interval energy	Btu/slug
V	velocity of orbiter	ft/sec
$\bar{V}$	velocity of meteoroid relative to radiator	ft/sec
w	coolant flow velocity	ft/sec
w_j	nondimensional radiosity, Eq. 6.21	-
W_j	radiosity	Btu/(hr ft^2)
x	distance from orbiter stagnation point to radiator panel	ft
x, z	rect. Cart. coordinates, see Fig. 4	ft
x_{ij}, x_{ijk}	auxiliary parameters, defined by Eqs. 6.10 and 6.11	-
y	overall length of radiator in direction parallel to gravity	ft
y	transverse fin coordinate	ft
z	axial distance	ft
Z	geometric altitude	ft

Greek Symbols

α	experimental meteoroid flux parameter, (Eq. 8.4)	$1/(ft^2 day\ gm^{\beta})$
α	thermal diffusivity	ft^2/hr
α_{ij}	total hemispherical absorptance	-
β	constant in atmospheric viscosity equation, (Eq. 3.7)	$kg/(sec\ mK^{1/2})$
β	experimental meteoroid flux parameter, (Eq. 8.4)	-
β	isobaric thermal expansion coefficient, see Eq. 3.5	1/R
γ	ratio of specific heats	-
δ	diameter-over-length ratio	-
δ_{ij}	Kronecker delta	-
ε	total hemisphere emittance	-
ζ	dimensionless axial distance, Eq. 3.19	-
η	dimensionless radius, Eq. 3.25	-
θ	dimensionless temperature, Eq. 3.21	-
θ	empirical constant (Eq. 8.1)	-
κ	isothermal compressibility, Eq. 3.4	ft^2/lbf
λ	angle between path of meteoroid and normal to protected surface (Eq. 8.6)	deg.
λ	wave length	ft
λ_1	parameter, defined by Eq. 4.11	-
λ_2	parameter, defined by Eq. 4.12	-
μ	dynamic viscosity	slug/(ft sec)
ν	dimensionless density	-
ν	kinematic viscosity	ft^2/sec
ξ	dimensionless x coordinate	-

π	dimensionless pressure, Eq. 3.22	
ρ	density	$slug/ft^3$
σ	Stefan-Boltzmann constant	$Btu/(hr\ ft^2\ R^4)$
τ	dimensionless time, Eq. 3.20	-
τ	time radiator is exposed to meteoroid environment	day
ϕ	angle between surface normal and radiation beam	-
ϕ	dimensionless property Eqs. 3.27-3.30, Eq. 4.4	-
ϕ, ϕ^*	polar angle in Eq. 6.15	-
ϕ_{Nc}	modified conduction parameter, Eq. 5.6	
ϕ	empirical constant (Eq. 8.1)	-
ϕ	dimensionless parameter, Eq. D. 13	-
χ	quadrature coefficient	-
ψ	circumferential fraction, defined by Eq. 4.3	-
ψ	residual, see Eqs. 12.1 and 12.2	-
ω	dimensionless velocity Eq. 3.23	-

Subscripts

aw	adiabatic wall
aero	aerodynamic
b	values at the endpoints of straight line segments of atmospheric temperature profile, (Table 5)
c	coolant fluid
c	critical value
c	enclosure
c_p	referring to specific heat at constant pressure

e	outer surface of meteoroid protection layer, (environment)
f	referring to friction factor
f	fin
F	Fourier number
i, j	position index
m	meteoroid protection layer
M	Mach number
net,rad	net radiant
p	meteoroid particle
p	referring to pressure
r	fin root
t	fin tip
t	target material
t	tubes
w	channel wall
w	surface or wall condition
z	axial distance
z	thermal equation of state
o	entrance (reference) conditions
o	sea level values
1	upper fin side
2	lower fin side
∞	free stream condition
ζ	partial differentiation with resp. to ζ
η	partial differentiation with resp. to η
κ	referring to compressibility

λ	monochromatic
τ	partial differentiation with respect to τ

Superscripts

*	evaluated at reference temperature T*

A. HEAT TRANSFER

1. Introduction

The objective of the radiator simulation is to predict both the transient and the steady state heat transfer characteristics under predetermined operating conditions, stationary in the former case and dynamic in the latter. Both cases were treated as initial value problems, and the principal governing equations are partial differential equations which are linear in the time-derivatives of first order at most.

Under stationary boundary conditions steady state will be reached, regardless of intial conditions*, as all partial derivatives with respect to time vanish on account of dissipative effects within the system. For the computer simulation of steady state conditions this means that the process of advancing in time can be discontinued as soon as all variables y_i , $i = 1, 2, \ldots N$, have reached their expected asymptotic values $(y_i)_\infty$ with sufficient accuracy, that is when for some chosen ε_i

$$\delta_i = |y_i - (y_i)_\infty| \leq \varepsilon_i \tag{1.1}$$

has been reached. The expected asymptotic values $(y_i)_\infty$ can be estimated on the basis of the recognition that for large enough values of the time, $t > t_M$

$$y_i \rightarrow (y_i)_\infty \pm ae^{-bt} \tag{1.2}$$

with, $a > 0$, $b > 0$, to be determined; $t > t_M$.

---

* Subject to certain continuity requirements which are discussed in Chapter III.

The evaluation δ_i during the numerical integration is covered in Chapter III.

The radiator system consists of four components:

(i) the fin

(ii) the coolant fluid

(iii) the coolant flow channel

(iv) the meteoroid protection layer.

Two coordinate systems were introduced (see Figure 4), one for the fin and the other for the flow channel and the meteoroid protection layer. The rectangular Cartesian system (x,z) for the fin has its z-axis parallel to the tube axis, starting at the inlet plane, and its x-axis passing through the line of profile symmetry, with x = 0 designating the root of the fin. Cylindrical coordinates (r,z) are used for both the tube and the meteoroid protection layer, with the z-axis along the tube.

The radiator system is describable in terms of the following six dependent state variables

(i) for the fin:

the fin temperature T (t;x,z)

(ii) for the coolant fluid:

the fluid temperature T (t;z)

the fluid pressure p(t;z)

the fluid velocity w(t;z)

(iii) for the fluid flow channel:

the tube wall temperature T (t;r,z)

(iv) for the meteoroid protection layer

the protection layer temperature T (t;r,z)

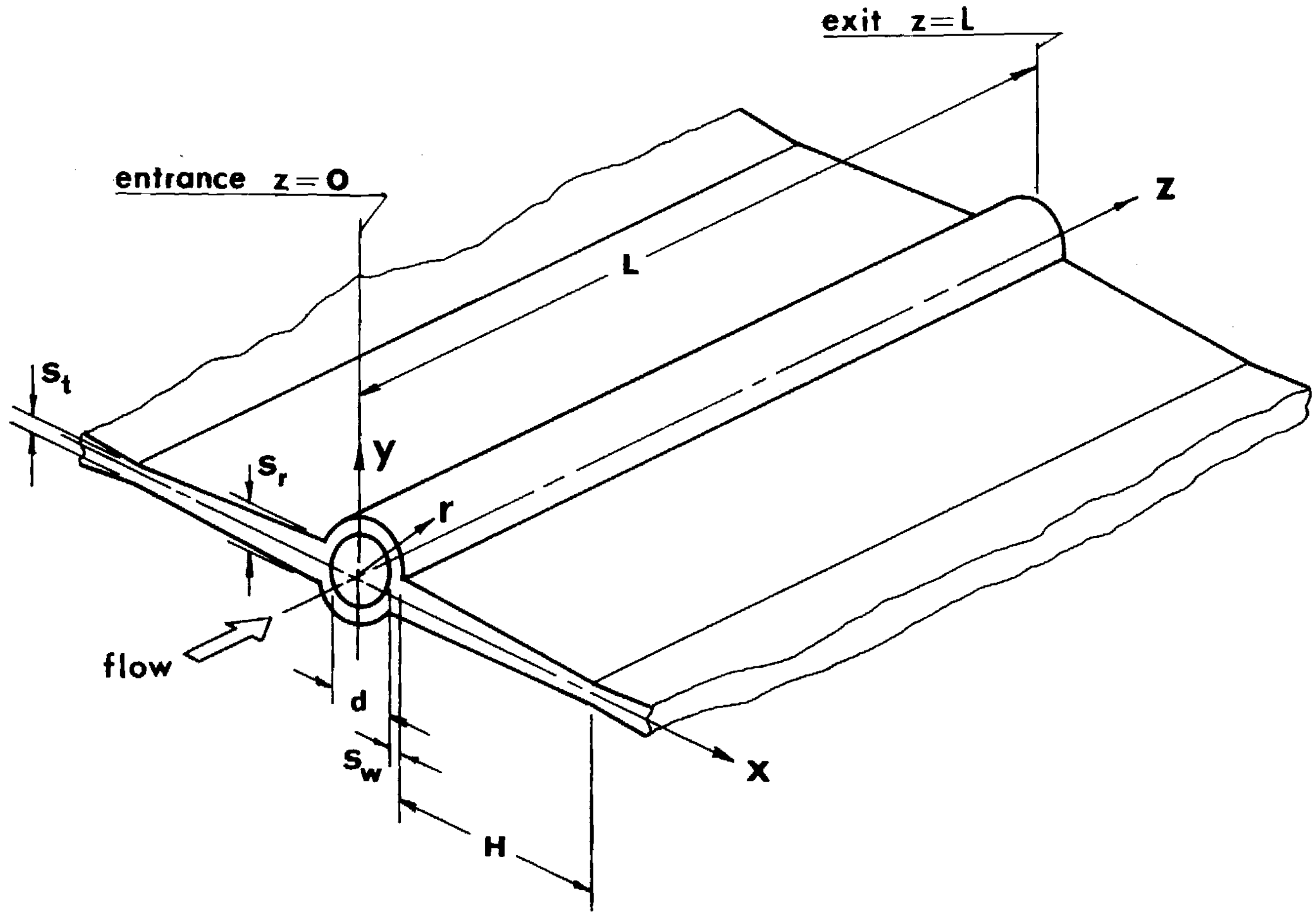

Figure 4. Fin Element and Coordinate System

These six dependent variables must satisfy four equations of energy conservation, one for each component of the system, further the equations of mass conservation and of momentum balance for the fluid. These conservation equations take on the form of partial differential equations subject to initial and boundary conditions. Finally, the energy conservation equation for the fin involves the net radiant and convective power fluxes leaving the fin.

In the following Sections, III A.2 through III A.7 are discussed, in that order, the six principal governing equations associated with the four system components listed above, the subsidiary equations governing the radiative heat exchange and, lastly, the convective heat transfer between coolant fluid and tube wall and between the fin and the atmosphere during ascent and reentry.

2. The Fin

The objective of this section is to develop the energy equation for the fin. The derivation is based on the assumptions that the thermal conductivity and specific heat of the fin material are functions of temperature while the fin density is constant. The energy balance for the fin accounts for both radiative and convective fluxes from the fin surfaces. The development of a method to predict the net radiant flux from the fin surfaces can be found in Section II.6. The procedure used for the evaluation of the convective flux from the fin surface is outlined in Section II.7.

The energy balance on a differential volume of the fin can be expressed as

$$\frac{\partial}{\partial x}\left[k_f A_x \frac{\partial T_f}{\partial x}\right] dx + \frac{\partial}{\partial z}\left[k_f A_z \frac{\partial T_f}{\partial z}\right] dz + q''_{net,rad} \quad A_s$$

$$q''_{aero} \quad A_s = \rho_f V c_{pf} \frac{\partial T_f}{\partial t} \tag{2.1}$$

where T is the fin temperature and the coordinate system is shown in Fig. 4. The areas A_x and A_z represent the cross-sectional areas of the fin perpendicular to the heat flow in the x and z directions, and A_s represents the total non-adiabatic surface area of the fin element. The symbol V is the volume of the fin element. The properties of the fin material are represented by the symbols k_f, ρ_f and c_{pf} which stand for the thermal conductivity, density and specific heat, respectively. The terms $q''_{net,rad}$ and q''_{aero} appearing in Eq. 2.1 denote the radiative and convective heat gain from the surroundings to the fin surfaces.

The first two terms in Eq. 2.1 constitute the net conduction of energy into the fin element. The third and fourth terms on the left hand side of the equation stand for the net radiation and convection gain, respectively, from the surfaces of the fin element. The term of the right hand side of the equation represents the storage of internal energy within the fin element.

The appropriate areas and the volume to be substituted into Eq. 2.1 are

$$A_x = 2[s_f - cx]\ dz \tag{2.2}$$

$$A_z = 2[s_f - cx]\ dx \tag{2.3}$$

$$A_s = dxdz/\left[c^2 + 1\right]^{1/2} \tag{2.4}$$

$$V = 2[s_f - cx]\ dxdz \tag{2.5}$$

where s_f is the fin half thickness at its root and c is the negative slope of the fin side surfaces.

Substituting Eqs. 2.2 through 2.5 into Eq. 2.1 and simplifying the resulting equation yields

$$\rho_f \, c_{pf} \, \frac{\partial T_f}{\partial t} = k_f \left[\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial z^2} \right] + \frac{dk_f}{dT} \left[\left(\frac{\partial T_f}{\partial x}\right)^2 + \left(\frac{\partial T_f}{\partial z}\right)^2 \right]$$

$$- \left(\frac{ck_f}{t-cx} \right) \frac{\partial T}{\partial x} + \frac{\sqrt{c^2+1}}{2(t-cx)} \left[q''_{net,rad} + q''_{aero} \right] \tag{2.6}$$

The Normalization of Eq. 2.6 is achieved by defining nine dimensionless quantities:

Let

$$\xi = x/H \tag{2.7}$$

$$\zeta = z/L \tag{2.8}$$

represent the nondimensional fin coordinate perpendicular and parallel to the tube, respectively. Then

$$\tau = tw_o/L \tag{2.9}$$

is the dimensionless time. The symbol w_o stands for the velocity of the coolant fluid entering the tube.

The nondimensional fin temperature is defined as

$$\theta_f(\tau,\xi,\zeta) = \frac{T_f(\tau,\xi,\zeta)}{T_o} \tag{2.10}$$

where T_o is the temperature of the coolant fluid entering the tube.

The dimensionless conduction parameter N_{Nc} and the Fourier number are defined as

$$N_{Nc} = H\sigma T_o^{\,3}/k_f \tag{2.11}$$

$$N_{Fo} = \frac{\alpha_f L}{w_o H^2} = \frac{k_f\, L}{\rho_f c_{pf} w_o H^2} \tag{2.12}$$

and the nondimensional geometrical quantities are defined as

$$\bar{s}_f = s_f/H \tag{2.13}$$

$$B(\xi) = 2(\bar{s}_f - c\xi) \tag{2.14}$$

$$D = (c^2 + 1)^{1/2} \tag{2.15}$$

where c is the negative slope of the fin side surfaces. For a non-tapered fin c is zero.

Both the net radiative and convective flux terms appearing in Eq. 2.6 are normalized by dividing each term by σT_o^4, or

$$\tilde{q}_{net,rad} = \frac{q''_{net,rad}}{\sigma T_o^4} \tag{2.16}$$

$$\tilde{q}_{aero} = \frac{q''_{aero}}{\sigma T_o^4} \tag{2.17}$$

The energy equation, Eq. 2.6, may now be written in terms of the nondimensional quantities given in Eqs. 2.7 through 2.17. The resulting nondimensional equation is

$$\dot{\theta}_f = N_{Fo} \left\{ (\theta_f)_{\xi\xi} + \left(\frac{H}{L}\right)^2 (\theta_f)_{\zeta\zeta} + \frac{T_o}{k_f} \frac{dk_f}{dt} \left[(\theta_f)_{\xi}^{2} + \left(\frac{H}{L}\right)^2 (\theta_f)_{\zeta}^{2} \right] \right. \tag{2.18}$$

$$\left. - 2 \frac{c}{B} (\theta_f)_{\xi} + \frac{D}{B} N_{Nc} [\tilde{q}_{net,rad} + \tilde{q}_{net,conv}] \right\}$$

The dot superscript appearing in Eq. 2.18 denotes differentiation with respect to nondimensional time and the subscripts ξ and ζ represent partial differentiation with respect to the dimensionless coordinates indicated.

The normalized energy equation, Eq. 2.18, defines the rate of change of the dimensionless fin temperature θ_f.

The Boundary Conditions for Eq. 2.18 are taken as follows:

(i) The fin root is at the temperature of the outside of the tube.

(ii) The fin tip is insulated.

(iii) The portion of the fin in contact with the inlet manifold is at the outside temperature of the manifold.

(iv) The portion of the fin in contact with the exit manifold is at the temperature of the outlet manifold.

Written in mathematical terms these four boundary conditions are

$$\theta_f(\tau,0,\zeta) = \theta_w(\tau,\xi_o,\zeta) \tag{2.19}$$

$$\frac{\partial \theta_f}{\partial \xi}(\tau,1,\zeta) = 0 \tag{2.20}$$

$$\theta_f(\tau,\xi,0) = \theta_w(\tau,\xi_o,0) \tag{2.21}$$

$$\theta_f(\tau,\xi,1) = \theta_w(\tau,\xi_o,1) \tag{2.22}$$

Implied in Eqs. 2.21 and 22 is, firstly, that the fluid temperature in the manifolds be equal to the fluid temperature at the tube inlet (inlet manifold) and at the tube exit (exit manifold) and that it remain unaltered along the manifold and vary only in time; secondly, that the temperature drop through the manifold wall be equal to that through the tube wall. The latter assumption is well justified because the temperature drop is exceedingly small.

It may be noted in connection with the boundary conditions that the radiative interactions action between manifold and fin as well as between manifold and tube are not taken into consideration at this time.

The Initial Condition for Eq. 2.18 may be any arbitrary relation representing a continuous temperature distribution over the fin, including the boundaries. The selection of the initial fin temperature distribution is left to the user.

3. The Coolant Fluid

The objective is to develop a unified treatment of all possible coolant fluids, that is gases, dielectric fluids and liquid metals. Three principal governing equations are sought which, together with the necessary thermodynamic and transport properties specified for each fluid of interest, define the fluid temperature T_c, the fluid pressure p (and thus the thermostatic state of the fluid) and the fluid velocity w, all as functions of time t and axial distance z.

The Continuity Equation for one dimensional flow through channels of constant cross-sections reads

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z} (\rho w) = 0 \qquad (3.1)$$

where ρ represents the fluid density. Replacing the density through the thermal equation of state

$$p = p\ (\rho,\ T_c) \qquad (3.2)$$

renders the continuity equation in terms of derivatives of the primary variables T_c, p and w:

$$\kappa \frac{\partial p}{\partial t} - \beta \frac{\partial Tc}{\partial t} = - \frac{\partial w}{\partial z} + w \left(\beta \frac{\partial Tc}{\partial z} - \kappa \frac{\partial p}{\partial z} \right) \qquad (3.3)$$

where κ and β stand for the isothermal compressibility and the isobaric expansion coefficient, respectively

$$\kappa = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial p}\right)_{Tc} \qquad (3.4)$$

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T_c}\right)_\rho \tag{3.5}$$

The Momentum Equation

$$\rho \frac{\partial w}{\partial t} + w\frac{\partial w}{\partial z} = -\frac{\partial p}{\partial z} - \frac{4f}{d}\rho\frac{w^2}{2} + \rho a_z \tag{3.6}$$

constitutes the balance between inertia forces on the left-hand side, pressure forces wall friction and external field forces (gravity) in axial direction, on the right-hand side of Eq. 3.6. The Fanning friction factor f is a function of the Reynolds-number $N_{Re} = d\ w / \nu$, where d and ν stand for the tube diameter and the kinematic viscosity, respectively and subscript o designates the fluid inlet conditions. The following relations are used to compute the Fanning friction factor:

for $N_{Re} < 2300$ (laminar flow

$$4f = \frac{64}{N_{Re}} \tag{3.7}$$

for $2300 \leq N_{Re} \leq 10^6$ (Ref. 1)

$$4f = 0.0054 + 0.396\ N_{Re}^{-0.3} \tag{3.8}$$

for $N_{Re} > 10^6$ (Ref. 2)

$$4f = 0.0032 + 0.221\ N_{Re}^{-0.237} \tag{3.9}$$

Equations 3.8 and 9 could be replaced by a single equation (Ref. 3)

$$4f = [0.86859 \ \ell n \frac{N_{Re}}{1.964 \ \ell n \ N_{Re}} - 3.8215]^{-2} \tag{3.10}$$

which, however, requiries more computational effort.

The Energy Equation. Let u, h, $\bar{h}_c$ and $T_w = T_w(t;\ r_i, k)$ represent, respectively the internal energy and the enthalpy of the fluid, the convective film coefficient and the tube wall temperature at the fluid-wall interface. For one-dimensional flow through channels of constant cross-section and with heating or cooling from the wall, conservation of energy requires that, with respect to a stationary reference frame

$$\frac{\partial}{\partial t} [\rho (u + \frac{w^2}{2})] + \frac{\partial}{\partial z} [\rho w \ (h + \frac{w^2}{2} + a_z z)] = \frac{4}{d} \bar{h}_c \ (T_w - T_c) + \frac{\partial}{\partial z} (k_c \frac{\partial T_c}{\partial z}) \tag{3.11}$$

The first term constitutes the storage of thermal and kinetic energies; the storage of potential energy, being negligibly small for expected accelerations, is ignored. The second term on the left-hand side stands for the convection of thermal, kinetic and potential energies as well as the power associated with the pressure. The right-hand side contains, firstly, the convective heat transfer from the channel wall to the fluid and, secondly, the axial heat conduction term which will later be shown to be negligibly small for all fluids. The factor 4/d in front of the convective heat transfer term results from the ratio of the channel circumference to the cross-sectional area, evaluated for a circular tube. The symbol k_c represents the thermal conductivity of the coolant.

Given a caloric equation of state

$$u = u(\rho, T_c) \tag{3.12}$$

or an equivalent expression for the specific heat, c_p , one can write, with the aid of Eqs. 3.2, 4 and 5

$$dh = c_p dT_c + \frac{1}{\rho} (1 - \beta T_c) \; dp \tag{3.13}$$

$$du = (c_p - \frac{p\beta}{\rho}) \; dT_c + \frac{1}{\rho} (\kappa p - \beta T) \; dp \tag{3.14}$$

and then recast Eq. 3.11 in terms of the derivatives of the principal variables T_c, p and w:

$$\rho \; c_p \frac{\partial T_c}{\partial t} - \beta T_c \frac{\partial p}{\partial t} + \rho w \frac{\partial w}{\partial t} = \frac{4}{d} \bar{h}_c \; (T_w - T_c)$$
$$+ \frac{\partial}{\partial z} (k_c \frac{\partial T_c}{\partial z}) - \rho w \; [c_p \frac{\partial T_c}{\partial z} +$$
$$\frac{1}{\rho} (1 - \beta T) \frac{\partial p}{\partial z} + w \frac{\partial w}{\partial z} + a_z] \tag{3.15}$$

Thus, three governing equations, Eqs. 3.3, 6 and 15, have been established which define the three principal variables T_c, p and w, provide the initial and boundary conditions are properly specified and the convective film coefficient can be predicted. Since the normalization of these equations, followed by an order-of-magnitude comparison will indicate that the conductive term in Eq. 3.15 is negligible so as to simplify the boundary conditions, the discussion of the inital and boundary conditions is deferred until after the normalization.

The convective film coefficient is computed from the following relationships between the Nusselt number $N_{Nu} = \bar{h}_c d/k_c$, the Reynolds number N_{Re} and the Prandtl number $N_{Pr} = \mu \, c_p/k_c$ where μ represents the dynamic viscosity:

For $N_{Pr} < 0.1$ (liquid metals)

$$N_{Nu} = 6.5 + 0.025 \; (N_{Re} \; N_{Pr})^{0.8} \tag{3.16}$$

which produces Nusselt numbers between those appropriate for uniform heat flux (Martinelli) and for uniform wall temperature (Seban and Shimazaki) (Ref. 4).

For $N_{Pr} > 0.1$ and

for $N_{Re} < 2300$ (laminar flow, Ref. 5)

$$N_{Nu} = 3.65 + \frac{0.0668 \; (N_{Re} N_{Pr} \delta)}{1 + 0.045 \; (N_{Re} N_{Pr} \delta)} \tag{3.17}$$

for $N_{Re} \geq 2300$ (turbulent flow, Ref. 5)

$$N_{Nu} = 0.116 \; (N_{Re}^{\;0.667} - 125) \; N_{Pr}^{\;0.333} \; (1 + \delta) \tag{3.18}$$

where $\delta = d/L$ stands for the tube diameter-over-length ratio.

The Normalization of Eqs. 3.3, 6 and 15 is carried out for the purpose of scaling and performing an order-of-magnitude comparison. The computational effort is also reduced in the process.

Let

$$\zeta = z/L \tag{3.19}$$

$$\tau = tw_o/L \tag{3.20}$$

represent the nondimensional axial distance and the nondimensional time, respectively, and let the dimensionless state variables be defined as

$$\theta_c\ (\tau,\zeta) = \frac{T_c(t,z)}{T_o} \tag{3.21}$$

$$\pi\ (\tau,\zeta\ ) = \frac{p\ (t,z)}{p_o} \tag{3.22}$$

$$\omega\ (\tau,\zeta\ ) = \frac{w\ (t,z)}{w_o} \tag{3.23}$$

and to represent the nondimensional temperature, pressure and velocity of the fluid, that is, the principal dependent fluid flow variables. The subscript "o" designates the constant reference state of the fluid at the tube entrance. Introduce next the nondimensional density

$$\nu(\tau,\ \zeta) = \frac{\rho(t,z)}{\rho_o}\ , \tag{3.24}$$

the nondimensional radial distance from the channel axis

$$\eta = \frac{2r}{d}, \tag{3.25}$$

and the nondimensional tube wall temperature

$$\theta_w(\tau;\eta,\zeta) = \frac{T_w(t;r,z)}{T_o} \tag{3.26}$$

Notice, that all dependent variables lie between zero and unity, except ν and ω whose product $(\nu\omega)$ remains essentially equal to unity with neither ν nor ω departing far from unity. The reference temperature T_o is, under normal operating conditions, the highest temperature in the system.

Furthermore, consider the following ϕ-values to vary along the channel axis:

$$\phi_\beta = T_o\beta \tag{3.27}$$

$$\phi_\kappa = p_o\kappa \tag{3.28}$$

$$\phi_{cp} = \frac{c_p}{c_p(\rho_o, T_o)} = \frac{c_p}{c_{p,o}} \tag{3.29}$$

$$\phi_k = \frac{k}{k(\rho_o, T_o)} = \frac{k}{k_o} \tag{3.30}$$

and, finally, the following constant F-parameters:

$$F_p = \frac{p_o}{\rho_o w_o^2} \tag{3.31}$$

$$F_f = 4f\,\frac{L}{d} = \frac{4f}{\delta} \tag{3.32}$$

$$F_z = \frac{p_o}{\rho_o c_{p,o} T_o} \tag{3.33}$$

$$F_M = F_z / F_p \tag{3.34}$$

Let the dot above a variable designate partial differential with respect to the nondimensional time τ and the subscript ζ partial differentiation with respect to the dimensionless axial coordinate ζ . Then the principal conservation equations, Eqs. 3.3, 6 and 15 read, respectively and in non-dimensional form:

$$\phi_\beta \; [\dot{\theta}_c + \omega(\theta_c)_\zeta \;] = \omega_\zeta + \phi_\kappa(\pi + \omega\pi_\zeta) \tag{3.35}$$

$$\omega = \omega \; \omega_\zeta = - \frac{F_p}{\nu} \; \pi_\zeta - F_f \frac{\omega^2}{2} \tag{3.36}$$

$$\begin{aligned} \dot{\theta}_c - F_z \frac{\phi_\beta}{\phi_{cp}} \; \frac{\theta_c}{\nu} + F_M \; \frac{1}{\phi_{cp}} \; \omega\omega_\zeta = \delta \frac{4N_{Nu}}{N_{Re}N_{Pr}} \; \cdot \frac{1}{\nu\phi_{cp}} (\theta_\omega - \theta_c) + \frac{\delta^2}{4N_{Nu}} \\ \times [\; \phi_\kappa(\theta_c)_\zeta \;]_\zeta \; - \omega(\theta_c)_\zeta + \\ F_z \; \frac{1-\theta_{c\beta}}{\phi_{cp}} \cdot \frac{1}{\nu} \pi_\zeta + F_M \; \frac{1}{\phi_{cp}} \omega \, \omega_\zeta \end{aligned} \tag{3.37}$$

These are the three equations which define the three time rates of change of

$\dot{\theta}_c$, $\dot{\pi}$ and $\dot{\omega}$. It can be seen from Eq. 3.37 that the axial conduction is always small of an order less than δ^2 (since $N_{Nu} > 3$) when compared with the convective term, unless the fluid should reach the wall temperature within the very first small fraction of the tube length. Axial conduction is hence ignored as $\delta^2 \approx 10^{-6}$, and the order of differentiation of Eq. 3.37 is reduced to one.

$$\dot{\theta}_c - F_z \frac{\phi_\beta}{\phi_{cp}} \frac{\theta_c}{\nu} \dot{\pi} + F_M \frac{1}{\phi_{cp}} \omega\dot{\omega} = \frac{4N_{Nu}}{\delta N_{Rc} N_{Pr}} \frac{\theta_\omega - \theta_c}{\nu_{cp}} - \omega(\theta_c)_\zeta + F_z$$

$$\frac{1 - \theta_{c\beta}}{\nu\phi_{cp}} \pi_\zeta + \frac{F_M}{\phi_{cp}} \omega\omega_\zeta \qquad (3.38)$$

The Boundary Conditions to be imposed on Eqs. 3.35, 36 and 38 are chosen, at the channel entrance, to be

(i) constant mass flow rate $\dot{m}$.

(ii) constant inlet pressure p_o.

(iii) continuous transition, of the inlet fluid temperature, from an initial temperature $\theta = \theta_i$ to the constant operational temperature $\theta(t,0) = 1$.

These boundary conditions accomodate the calculation of the steady state conditions as well as of the most likely start-up operation toward stationary operating conditions. Notice that there are no step changes implied in any of the dependent variables which is essential for the numerical integration. Writing these boundary conditions more specifically one gets

at $\zeta = 0$

$$\theta\ (\tau,\ 0) = 1 - (1 - 0_i)\ e^{-7\tau} \tag{3.39}$$

$$\pi\ (\tau,\ 0) = 1 \tag{3.40}$$

$$\omega\ (\tau,\ 0) = \frac{1}{\nu(\pi,\ \theta)} \tag{3.41}$$

Here, the time constant was chosen arbitrarily so as to have the fluid reach, within o.1%, its steady inlet temperature at the inlet during the time interval that it takes a fluid particle to pass through the channel. Equation 3.41 is given through the thermal equation of state, Eq. 3.2.

The Initial Conditions appropriate to the system of Eqs. 3.35, 36 and 38 are derived from the requirement that the flow should initially be at steady state with the fluid inlet temperature equal to the uniform channel wall temperature. Setting the time derivatives equal to zero in Eqs. 3.35, 36 and 38 results in a system of three ordinary differential equations which are linear in $d\pi/d\zeta$, $d\theta_c/d\zeta$ and $d\omega/d\zeta$:

$$F_p\ \frac{d\pi}{d\zeta} + \frac{d\omega}{d\zeta} = -F_f\ \nu\ \frac{\omega^2}{2} \tag{3.42}$$

$$F_z\ \frac{\phi_\beta}{\nu}\ \frac{d\pi}{d\zeta} + \frac{d\theta_c}{d\zeta} + \frac{F_M}{\phi_{cp}}\ \omega\ \frac{d\omega}{d\zeta} = \frac{4N_{Nu}}{\delta N_{Rc} N_{Pr}}\ (\theta_w - \theta_c) \tag{3.43}$$

$$\phi_\kappa\ \frac{d\pi}{d\zeta} - \phi_\beta\ \frac{d\theta_c}{d\zeta} + \frac{1}{\omega}\ \frac{d\omega}{d\zeta} = 0 \tag{3.44}$$

These equations can be solved subject to the boundary conditions

$$\text{at } \zeta = 0 \qquad \left.\begin{aligned} \pi &= 1 \\ \theta_c &= \theta_i \\ \omega &= \frac{1}{\nu(\pi,\ \theta_c)} \end{aligned}\right\} \tag{3.45}$$

provided the function $\theta_w = \theta_w\ (0;\ 1, \zeta)$ prescribing the initial channel wall temperature is specified. For the present analysis θ_w was set equal to θ_i. Equations 3.42 through 3.45 define the initial flow field.

Quasi-Steady Flow. It may be recognized that the momentum transport takes place at a much smaller time scale than the transport of thermal energy in that the pressure and the velocity fields adjust virtually instantaneously to a change in flow inlet conditons while the response of the temperature field to a change in channel wall temperature takes considerably longer, the reason being that the pressure perturbations propagate along the channel with the speed of sound. Unless one is specifically interested in the motion of sound waves one may consider the dynamics of the flow field, that is the pressure and velocity distributions, as part of the boundary conditions and imposed instantly and adiabatically by the flow inlet conditions.

The fluid temperature remains stationary during the dynamic adjustment and the time rate of change of both pressure and temperature remain small since ordinarily the pressure gradient remains balanced by the wall shear (and by the convective acceleration in the case of a gaseous coolant medium). Consequently, Eqs. 3.42 and 44 may serve to establish the pressure and velocity fields at all times, subject to boundary conditions given by Eqs. 3.40 and 3.41 while the temperature field remains defined by Eqs. 3.35, 36, 38 and the initial conditions discussed above. Particularly, solving Eqs. 3.35, 36 and 38 for $\dot{\theta}_c$ gives the differential equation which governs the temperature field:

$$\dot{\theta}_c = \frac{1}{1 - \frac{F_z}{\phi_{cp}} \frac{\phi_\beta^2}{\phi_\kappa} \frac{\theta}{\nu}} \left\{ \frac{4N_{Nu}}{\delta N_{Re} N_{Pr}} (\theta_w - \theta_c) \right.$$

$$+ F_z \frac{\phi_\beta}{\phi_{cp} \phi_\kappa} \times \left[\phi_\beta \, \omega(\theta_c)_\zeta - \frac{\theta_c}{\nu} \omega_\zeta \right]$$

$$\left. - \omega[(\theta_c)_\zeta + F_M F_f \frac{1}{\phi_{cp}} \frac{\omega^2}{2}] \right\} \qquad (3.46)$$

This completes the discussion of the development of the governing differential equations for the coolant fluid. All equations are solved numerically as discussed in Chapter III. The thermodynamic properties c_p, β, and κ are derived from the thermal equation of state, Eq. 3.2 and from the zero-pressure specific heat or other available properties. All thermodynamic functions as well as the transport properties κ and μ are considered, in general, as functions of two state variables, that is, of ρ and T or of p and T, as discussed in Section C of Chapter II.

4. The Flow Channel

The flow channel is treated as a circular tube with inner radius $r_i = d/2$ and outer radius $r_o = r_i + s_t$. The tube wall temperature $T_w(t;r,z)$ is defined through the familiar equation of energy conservation, written for the case of circular symmetry:

$$\frac{\partial T_w}{\partial t} = \alpha_w \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T_w}{\partial r}\right) + \frac{\partial^2 T_w}{\partial z^2} \right] + \frac{1}{(\rho c)_w} \frac{dk_w}{dT} \left[\left(\frac{\partial T_w}{\partial r}\right)^2 + \left(\frac{\partial T_w}{\partial z}\right)^2 \right], \tag{4.1}$$

where α_w represents the thermal diffusivity of the wall material and $(\rho c)_w$ its volumetric heat capacity. The boundary conditions are

at $r = r_i$

$$\bar{h}_c \, (T_w - T_c) = k_w \frac{\partial T_w}{\partial r} \tag{4.2}$$

at $r = r_o$

$$k_w \frac{\partial T_w}{\partial r} - \psi k_f \frac{\partial T_f}{\partial x} - (2\pi - \psi)\, k_m \frac{\partial T_m}{\partial r} = 0 \tag{4.3}$$

Here

- $\bar{h}_c$ is the convective film coefficient,
- T_c the fluid temperature,
- k the thermal conductivity,
- ψ the portion of outer tube circumference in contact with fins, expressed in radians,

and the subscripts w, f and m designate, respectively, tube wall, fin and meteoroid protection layer. Equations 4.2 and 3 constitute the continuity of the heat flux at the fluid-wall interface and at the wall-fin and wall-protection layer interfaces. Circumferential temperature variations are ignored.

After introducing

$$\eta = \frac{r}{r_i}, \quad \zeta = \frac{x}{H}; \quad \tau = \frac{tw_o}{L}; \quad \theta_w = \frac{T_w}{T_o},$$

$$\phi_c = \frac{k_c}{k_w}, \quad \phi_f = \frac{k_f}{k_w} \frac{r_i}{H},$$

$$\phi_m = \frac{k_m}{k_w} \qquad N_{Bi} = \frac{\bar{h}_c d}{k_w}, \tag{4.4}$$

$$\delta = \frac{d}{L}, \quad \phi_{\kappa w} = \frac{T_o}{k_w} \frac{dk_w}{dT}, \quad \phi_{Fo,w} = \frac{\alpha_w L}{w_o r_i^2}$$

with H representing the fin height, that is, the distance between the fin root and fin tip, one may recast Eqs. 4.1, 2 and 3 to read

$$\dot{\theta}_w = \phi_{Fo,w} \left\{ \frac{1}{\eta} \frac{\partial}{\partial \eta} \left(\eta \frac{\partial \theta_w}{\partial \eta} \right) + \left(\frac{\delta}{2}\right)^2 \frac{\partial^2 \theta_w}{\partial \zeta^2} \right.$$

$$\left. + \phi_{\kappa w} \left[\left(\frac{\partial \theta_w}{\partial \eta}\right)^2 + \left(\frac{\delta}{2}\right)^2 \left(\frac{\partial \theta_w}{\partial \zeta}\right)^2 \right] \right\} \tag{4.5}$$

at $\eta = 1$

$$\frac{1}{2} N_{Bi} (\theta_w - \theta_c) = \frac{\partial \theta_w}{\partial \eta} \tag{4.6}$$

at $\eta = \eta_o$

$$\frac{\partial \theta_w}{\partial \eta} - \psi \phi_f \frac{\partial \theta_f}{\partial \xi} - (2\pi - \psi)\, \phi_m \frac{\partial \theta_m}{\partial \eta} = 0 \tag{4.7}$$

The superscript dot represents partial differentiation with respect to nondimensional time τ . As before in the treatment of the coolant fluid one recognizes that, with $\delta^2 \simeq 10^{-6}$, axial conduction remains insignificant. Thus, Eq. 4.5 takes on this final form

$$\dot{\theta}_w = \phi_{Fo,w} \left\{ \frac{1}{\eta} \frac{\partial}{\partial \eta} \left(\eta \frac{\partial \theta_w}{\partial \eta}\right) + \phi_{kw} \left(\frac{\partial \theta_w}{\partial \eta}\right)^2 \right\} \tag{4.8}$$

Equations 4.6, 7 and 8 define the tube wall temperature, provided Eqs. 4.6 and 7 hold at some initial time and the initial temperature $\theta_w\,(0;\eta,\zeta)$ is prescribed as a sufficiently smooth function of η and ζ .

Low Biot Number. When one compares possible heat fluxes at the fluid-wall interface with the possible radiant fluxes from the outer surface of the meteoroid protection layer covering the tube, one concludes that the maximum fluxes occur at the inner tube wall and that the Biot number N_{Bi} in Eq. 4.6 is the largest ratio to be expected of external to internal thermal conductances. Thus, if N_{Bi} is small, say less than 0.05 (Ref. 6), then the temperature variation inside the tube wall is too small for experimental detection and a computation of the detailed temperature distribution on the basis of Eq. 4.8 cannot be justified as the associated computational effort is considerable.

In cases where the equivalent Biot number, representing the total thermal resistance within the channel wall and the protection layer, is small, the tube, the protection layer and a representative portion of the fin root are combined into a single control volume as depicted in Fig. 5. The equivalent Biot number $\bar{N}_{Bi}$ and the chosen limit are

$$\bar{N}_{Bi} = N_{Nu} \frac{k_c}{d} \left(\frac{s_w}{k_w} + \frac{s_m}{k_m}\right) < 0.05 \qquad (4.9)$$

where s_w and s_m stand for, respectively, the tube wall and the protection layer thicknesses. The combined volumetric heat capacity per unit of axial distance for the control volume consists of three parts, the first one for the tube wall, the second for the protection layer and the third for the first half fin element:

$$\pi d \ (\rho cs)_w \left\{ (1 + \frac{s_w}{d}) + (1 + 2 \frac{s_w}{d} + \frac{s_m}{d}) \frac{(\rho cs)_m}{(\rho cs)_w} + \frac{\Delta x}{\pi d} \ \frac{s_r}{s_w} \times \right.$$

$$\left. [1 - \frac{\Delta\xi}{4} (1 - \frac{s_t}{s_r})] \frac{(\rho c)_f}{(\rho c)_w} \right\} = \lambda_1 \ \pi d \ (\rho cs)_w \qquad (4.10)$$

where the subscripts w, m, f, r and t designate, respectively, parameters of the tube wall, the meteoroid protection layer, the fin, the fin root and the fin tip and where

- d is the tube diameter,
- ρ the density,
- s the thickness,
- Δx the node spacing on the fin, and
- $\Delta\xi = \Delta x/H$, the nondimensional node spacing

Heat enters the control volume, per units of time and axial distance,

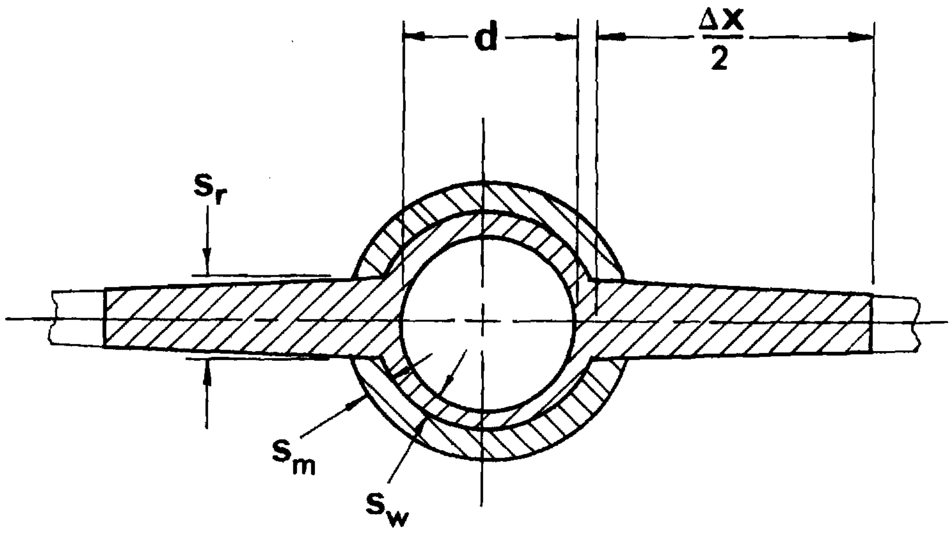

Figure 5. Control Volume for Low-Biot Number Cases

by convection from the fluid

$$\pi d\ \bar{h}_c\ (T_w - T_c),$$

and by convection and/or radiation from outside

$$(2\pi - \psi)\ (\frac{d}{2} + s_w + s_m)\ q''_m + \Delta x\ (q''_1 + q''_2)_f$$

where the subcripts 1 and 2 designate upper and lower fin sides, respectively, and where q" represents the sum of the convective and of the net radiant fluxes <u>entering</u> the outer surfaces. In the case of q''_m, the average over upper and lower portions of the outer circumference is to be taken.

Heat leaves the control volume through the fin by conduction, again per units of time and axial distance

$$2(s\ \frac{\partial T}{\partial x})_f$$

evaluated at $x = \Delta x/2$.

Combining the last four expressions into the energy balance leads to this expression

$$\lambda_1\ \pi d\ (\rho cs)_w \frac{\partial T_w}{\partial t} = \pi d\ \bar{h}_c\ (T_w - T_c) + \pi d\ \lambda_2\ q''_m + \Delta x\ (q''_1 + q''_2)_f + 2\ (s\ \frac{dT_f}{dx})\Big|_{\frac{\Delta x}{2}} \tag{4.11}$$

where λ_1 is defined by Eq. 4.10 and

$$\lambda_2 = (2 - \frac{\psi}{\pi})\ (\frac{1}{2} + \frac{s_w + s_m}{d}) \tag{4.12}$$

Equation 4.11 replaces Eqs. 4.6, 7 and 8 as well as Eqs. 5.3, and 5 governing the temperature distribution in the meteorroid protection layer and, lastly, Eq. 2.19 which constitutes one of the boundary conditions for the differential equation governing the fin temperature distribution. The only condition under which all the above equations may be replaced by the single equation, Eq. 4.11, is given by Eq. 4.9. Finally, it may be noted that Eq. 4.11 could also be normalized but since no new dimensionless groups result from such normalization it is omitted here.

5. The Meteoroid Protection Layer

The differential equation governing the temperature distribution within the meteoroid protection layer which covers the flow channel, is identical to that for the channel wall, Eq. 4.8, except for the two dimensionless parameters, the Fourier coefficient ϕ_{Fo} and the conductivity temperature coefficient ϕ_k which now must be evaluated for the protection layer material:

$$\phi_{Fo,m} = \frac{\alpha_m}{\alpha_w} \phi_{Fo,w} \tag{5.1}$$

$$\phi_{k,m} = \frac{T_o}{k_m} \frac{dk_m}{dT} \tag{5.2}$$

After ignoring the axial conduction for the reasons stated in Section 4 one obtains as the nondimensional energy conservation equation

$$\dot{\theta}_m = \phi_{Fo,m} \left\{ \frac{1}{\eta} \frac{\partial}{\partial \eta} \left(\eta \frac{\partial \theta_m}{\partial \eta} \right) + \phi_{k,m} \left(\frac{\partial \theta_m}{\partial \eta} \right)^2 \right\} \tag{5.3}$$

Two boundary conditions are required, one of which is given by Eq. 4.7 while the other one is dictated by the heat flux continuity at the outer boundary:

at $r = r_e$

$$k_m \frac{\partial T_m}{\partial r} = q''_m \tag{5.4}$$

where q'' is defined as the net flux <u>entering</u> both by radiation and/or aerodynamic heating. Equation 5.4 reads in nondimensional form at $\eta = \eta_e$

$$\frac{\partial \theta_m}{\partial \eta} = \phi_{Nc} \, (\tilde{q}_{net,rad} + \tilde{q}_{aero}) \tag{5.5}$$

with ϕ_{Nc} representing a local conductance parameter

$$\phi_{Nc} = \frac{\sigma d T_o^3}{2k_m} \tag{5.6}$$

and

$$\tilde{q}_{net,rad} = \frac{q''_{net,rad}}{\sigma T_o^4} \tag{5.7}$$

$$\tilde{q}_{aero} = \frac{q''_{aero}}{\sigma T_o^4} \tag{5.8}$$

Here, σ represents the Stefan-Boltzmann constant, and $q''_{net,rad}$ and q''_{aero} the net radiant incident heat flux and the convective heat flux, respectively.

If the initial temperature distribution is given and if Eqs. 4.7 and 5.5 hold initially then the protection layer temperature θ is completely defined as a funtion of time and location by Eqs. 5.3, 5 and 4.7, provided the incident radiation and the aerodynamic heating are prescribed as functions of time. The prediction of these incident heat fluxes is discussed in Section 6 and 7 of this Chapter.

In the case of low Biot numbers at the coolant fluid-tube wall interface the meteoroid protection layer is lumped together with the tube wall as discussed in Section 4 of Chapter II.

6. Radiation

The objective of this section is to develop a procedure by which to predict the net radiant heat flux incident on fin and tube surfaces which are exposed to any combination so solar, albedo and planetary irradiation. Included into the assessment of radiative transfer is the radiative energy exchange between fin panel and flow channel or its protective coating as well as the effect of structural panels in the vicinity of the fin system; however not included is any possible gas radiation as could conceivably by encountered during reentry.

In seeking the proper mathematical model it is recognized, firstly, that the prevailing thermal radiant energy lies in either the visible (solar irradiation) or the infrared portion of the spectrum, and, secondly, that the fin system is coated, for the purpose of optical optimization, with a dielectric paint. Consequently, spectrally dependent optical properties must be dealt with, but, for the latter reason, the transfer matrix of radiative exchange can be expected to remain temperature insensitive over some range of operational conditions, a fact which is very much appreciated from the computational view point.

For the analysis, the fin surface A_f , the outer surface on the flow channel A_n, and the structural surface(s) A_n , are all considered as parts of an enclosure C which is completed by a set of arbitrarily concave, non-reflecting imaginary surfaces A_e which connect A_m, A_f and A_n and along which is specified the emerging net radiant heat flux representing solar, albedo and planetary irradiation. The sum $A_m + A_f + A_n + A_e$ is the inner surface A_c of the enclosure

Three steps are necessary for the prediction of the incident net radiant heat flux $q''_{net,rad}$. Firstly, the elemental exchange areas*

$$\frac{\partial^2 \overline{s_i s_j}}{\partial A_i \partial A_j} = \frac{\cos\phi_i \cos\phi_j}{\pi r^2} \tag{6.1}$$

need to be computed on the basis of the geometric relation between fin panels and flow channels. Here, the symbol r designates the distance between two area elements dA_i and dA_j which are visible from each other, and ϕ_i and ϕ_j represent the respective angles between r and the surface normals on dA_i and dA_j . The next step is to compute, from its definition, the radiosity or leaving radiant flux density, W_j:

$$W_j = \int_0^\infty W_{j,\lambda}\, d\lambda = \int_0^\infty \varepsilon_{j,\lambda} E_{j,\lambda}\, d\lambda + \int_{A_c} \frac{\partial^2 \overline{s_i s_j}}{\partial A_i \partial A_j} \int_0^\infty (1 - \varepsilon_{j,\lambda}) W_{i,\lambda}\, d\lambda \quad dA_i \tag{6.2}$$

where $W_{j,\lambda}$, $E_{j,\lambda}$ and $\varepsilon_{j,\lambda}$ stand for the monochromatic radiosity, the monochromatic black body emissive power

$$E_{j,\lambda} = \frac{2\, hc^2 n^2}{\lambda^5} \frac{1}{e^{(hc)/(k\lambda T_j)} - 1} \tag{6.3}$$

* For terminology and notations consult Ref. 7, Chapter 2.

and the monochromatic hemispherical emittance, respectively; the subscripts i and j designate two discrete points on A_c , and λ represents the wavelength. The Eq. 6.3 constitutes Planck's law of monochromatic emissive power intensity; h, c and k stand for, respectively, Planck's constant, the speed of light in vacuo and the Boltzmann constant. The third and last step is to calculate, on the basis of local energy balance, the net incident heat flux

$$(q''_{net,rad})_j = \int_0^\infty q''_{j,\lambda}\, d\lambda = \int_{A_c} (W_i - W_j)\, \frac{\partial^2\, \overline{s_i s_j}}{\partial A_i \partial A_j}\, dA_i \qquad (6.4)$$

It should be obvious that Eqs. 6.1, 2 and 4 contain all the necessary fundamental principles but their evaluation will introduce a number of simplifications and modifications, each selected for the particular system of interest. Specifically, Eq. 6.4 will have to supplement Eq. 6.2 for portions of A_c where the heat flux is specified. More importantly however, there is a choice to be made in view of the computational process regarding particularly Eq. 6.2. One may either solve the monochromatic version of Eq. 6.2 n times for the n significant spectral intervals encountered and thus face the ultimate task of solving n x N simultaneous linear algebraic equations when N discrete points on A_c need to be considered (possibly at several time steps during the calculation process) and then integrate the resluting total interchange areas over the spectrum (see Ch. 5.6 of Ref. 7).

Or, one may force the non-gray surface analysis into a gray surface analysis by placing the burden of complexity on the evaluation of appropriate optical properties. Both techniques afford any desirable accuracy of allowing for the spectral differences in surface properties, limited only by available calculation time; but the latter technique was chosen because, as a result of this choice, the complexity remains at peripheral parts of the computer code which are more accessible for later modifications toward greater sophistication, also the complexity may turn out, in almost all cases, to reduce partly to simple hand claculations.

After introducing

$$\varepsilon_i = \frac{\int_o^\infty \varepsilon_{i,\lambda} E_{i,\lambda} \, d\lambda}{\int_o^\infty E_{i,\lambda} \, d\lambda} = \frac{1}{E_i} \int_o^\infty \varepsilon_{i,\lambda} E_{i,\lambda} \, d\lambda \tag{6.5}$$

$$\alpha_{ij} = \frac{\int_o^\infty \varepsilon_{i,\lambda} W_{j,\lambda} \, d\lambda}{\int_o^\infty W_{j,\lambda} \, d\lambda} \tag{6.6}$$

Equation 6.2 simplifes to

$$W_j = \varepsilon_j E_j + \int_{A_c} \frac{\partial^2 \overline{s_i s_j}}{\partial A_i \partial A_j} (1 - \alpha_{ij}) W_i \, \partial A_i \qquad (6.7$$

which reduces to the gray-surface radiosity equation whenever Eq. 6.6 reduces to $\alpha_{ij} = \varepsilon_i$. The difficulty now lies in evaluating Eq. 6.6 even though the radiosity $W_{j,\lambda}$ is as yet unknown.

By successively substituting the right-hand side of Eq. 6.2, in its monochromatic form, for $W_{i,\lambda}$ on the right-hand side of that equation, one obtains first (Ref. 8)

$$W_{j,\lambda} = \varepsilon_{j,\lambda} E_{j,\lambda} + (1 - \varepsilon_{j,\lambda}) \left\{ \int_{A_c} \frac{\partial^2 \overline{s_i s_j}}{\partial A_i \partial A_j} \left[\varepsilon_{i,\lambda} E_{i,\lambda} + (1 - \varepsilon_{i,\lambda}) \int_{A_c} \left(\frac{\partial^2 \overline{s_i s_m}}{\partial A_i \partial A_m} \varepsilon_{m,\lambda} E_{m,\lambda} + \dots \right) dA_m \right] dA_i \right. \tag{6.8}$$

and subsequently α_{ij} as the quotient of two infinite series. Since the enclosure radiation is dominated by the fin-sun and fin-sky interaction and since Eq. 6.8 contributes significantly only to the fin-flow channel interaction, the infinite series in Eq. 6.8 may be terminated after two terms (two reflections; the resulting error is less than the uncertainty in ε_λ), and Eq. 6.6 becomes:

$$\alpha_{ij} = \frac{X_{ij} E_j + \int_{A_c} \frac{\partial^2 \overline{s_j s_k}}{\partial A_j \, \partial A_k} E_k (X_{ik} - X_{ijk}) \, dA_k}{\varepsilon_j E_j + \int_{A_c} \frac{\partial^2 \overline{s_j s_k}}{A_i \, A_k} E_k (\varepsilon_k - X_{jk}) \, dA_k} \tag{6.9}$$

where

$$X_{ij} = \int_0^\infty E_{j,\lambda} \, \varepsilon_{j,\lambda} \, \varepsilon_{i,\lambda} \, d\lambda \Big/ E_j \tag{6.10}$$

$$X_{ijk} = \int_0^\infty E_{k,\lambda}\, \varepsilon_{k,\lambda}\, \varepsilon_{j,\lambda}\, \varepsilon_{i,\lambda}\, d\lambda \Big/ E_k \tag{6.11}$$

In cases where the net radiant flux is specified over portions of A , the emissive power E is to be replaced by the net radiant flux q'' in Eqs. 6.9, 10 and 12, which results in one additional term each in the numerator and the denominator of Eq. 6.9.

In summary, the incident net radiant heat flux for the diffuse, non-gray enclosure is calculated on the basis of an approximate gray-surface analysis in accordance with Eq. 6.4, 7 and 9 through 11. The spectral differences of the surfaces are accounted for in Eqs. 9 through 11. The remainder of this section is devoted to the solution of the radiosity equation, Eq. 6.7.

Recalling that A_c is the sum $A_m + A_n + A_f + A_e$ of the outer channel surface A_m , the possibly present, nearby structural surfaces A_n, the fin surface A_f , and the remainder of the enclosure A_e, one recognizes that the integrals over A_c in Eqs. 6.4, 7 and 9 need to be evaluated twice for each of the four parts, namely once with j = 1 representing the fin area and then with j = 2 for the exposed channel area. Since the incident solar, albedo and planetary radiant flux intensities are uniform over the fin area and averaged over the circumference of the channel area

$$\int_{A_e} \frac{\partial^2 \overline{s_i s_1}}{\partial A_i \partial A_1} (1 - \alpha_{i1})\, W_i dA_i = (1 - \alpha_{e1})\, q''_{e1} \tag{6.12}$$

$$\int_{A_e} \frac{\partial^2 \overline{s_i s_2}}{\partial A_i \partial A_2} (1 - \alpha_{i2}) W_i dA_i = (1 - \alpha_{e2}) q''_{e2} \tag{6.13}$$

where q" designates incident solar, albedo and planetary heat fluxes, appropriately averaged over a chosen area element. Should any structural surfaces obstruct the incident radiant fluxes ($A_n \neq 0$) then the right-hand sides of Eqs. 6.12 and 13 would have to be modified and reduced in the shaded portions of A_1 and A_2 ; and, if there are m such surfaces,

$$\int_{A_n} \frac{\partial^2 \overline{s_i s_j}}{\partial A_i \partial A_j} (1 - \alpha_{ij}) W_i dA_i = \sum_{k=1}^{m} \frac{\partial \overline{s_k s_j}}{\partial A_j} (1 - \alpha_{kj}) W_k , \tag{6.14}$$

$$j = 1, 2, \ldots m + 2.$$

Obviously, the radiosity and the temperature are assumed to be uniform over each structural component. No such structural components were considered in the program phase being reported on here, and Eq. 6.14 is taken to be zero.

This leaves only the integrals over A_m and A_f to be discussed. Moreover, since Eq. 6.1 is symmetric with respect to its subscripts i and j, the elemental exchange area is to be evaluated only once.

Considering first the fin, that is j = 1 and i = 2, and the fact that over the channel surface the radiosity and the temperature are considered to be functions of axial distance only

$$\int_{A_2} \frac{\partial^2 \overline{s_1 s_i}}{\partial A_1 \partial A_i} (1 - \alpha_{1i}) W_i \, dA_i =$$

$$\int_{z=0}^{z=L} [1 - \alpha_{1i}(z)] \, W_i(z) \int_{\phi=0}^{\phi^*} \frac{\partial}{\partial A_1} \left(\frac{\overline{s_1 s_i}}{\Delta A_1} \right) R d\phi \, dz = \tag{6.15}$$

$$\int_{z=0}^{z=L} [1 - \alpha_{1i}(z)] \, W_i(z) \, SS(z; x_f, z_f) \, dz$$

where L designates the tube length; R and ϕ are the polar coordinates of A_2 , with origin on the tube axis, with $\phi = 0$ and $\phi = \phi^*$ representing, respectively, the root of the fin and the contact line between the tube and its tangent plane through the center of ΔA_1 on the fin. The first step in Eq. 6.15 was obtained by integrating over ΔA_1 and subsequently applying the mean-value theorem of integral calculus, while the second step simply defines the exchange function for every point (x_f, z_f) on the fin which was integrated in closed form for the right-circular flow channel. The result is shown in Appendix D.

The exchange function of the tube with respect to the fin is obtained by dividing SS in Eq. 6.15 by (R_ϕ^*). Thus

$$\int_{A_1} \frac{\partial^2 \overline{s_2 s_i}}{\partial A_2 \partial A_i} (1 - \alpha_{2i}) W_i \, dA_i =$$

$$\frac{1}{R\phi^*} \int_{z=0}^{L} \int_{x=0}^{H} [1 - \alpha(z, x_f, z_f)] \, W(x_f, z_f) \, SS(z, x_f, z_f) \, dx_f \, dz_f \tag{6.16}$$

For the numerical evaluation of the integrals a suitable quadrature such as the trapezoidal rule is chosen so as to render Eq. 6.7 in this form

$$P_j = \sum_j M_{ji} W_i \qquad i,j = 1, 2, \ldots, N \tag{6.17}$$

which is a system of N linear algebraic equations for the $N = (n_x + 1) \times (n_z + 2)$ unknown values of the raidosity W_i. Here, n_x and n_z are the numbers of subdivisions chosen in the x- and the z- directions, respectively. The vector P on the left-hand side of Eq. 6.17 is called the exitation vector

$$P_j = -\varepsilon_j E_j - (1 - \alpha_{ej}) q''_{ej} \tag{6.18}$$

on the right-hand side, the transfer matrix M_{ji} is given by

$$\delta_{ji} - \chi_{\underline{i}} [1 - \alpha_{\underline{ji}}] SS_{\underline{ji}} = M_{ji} \tag{6.19}$$

where

$$\delta_{ji} = \begin{matrix} 0 \\ 1 \end{matrix} \quad \text{for} \quad \begin{matrix} i \neq j \\ i = j \end{matrix}$$

is the Kronecker delta, χ_i is a suitable quadrature coefficient and $SS_{\underline{ji}}$ is given either by Eq. 6.15 or by Eq. 6.16 depending on whether j refers to the fin or to the channel, respectively. There is no matrix multiplication implied in Eq. 6.19, hence the underscores.

In the present program phase, Eq. 6.17 is solved at every time step only when the transfer matrix is sufficiently temperature sensitive, otherwise the transfer matrix is completely inverted only once to yield the unknown radiosity at any time.

$$W_i = \sum_j (M_{ij})^{-1} P_j \tag{6.20}$$

through a simple matrix multiplication. It may be noted that the most significant temperture dependence of optical properties is contained in the exitation vector P_j.

All radiant heat fluxes are normalized with respect to σT_o^4 where T_o designates the reference temperature, that is the fluid inlet temperature. Exchange factors are nondimensional and need not be normalized.

$$w_j = \frac{W_j}{\sigma T_o^4}, \quad \tilde{q}_j = \frac{q''_j}{\sigma T_o^4}, \quad p_j = \frac{P_j}{\sigma T_o^4} \tag{6.21}$$

The nondimensional forms of Eqs. 6.4 and 6.20 are used to compute $\tilde{q}_{net,rad}$ in Eqs. 2.17, 4.11 and 5.5.

7. Aerodynamic Heating

The aerodynamic heating model used to evaluate the convective flux from the radiator surface on the orbiter vehicle is subdivided into three major regimes. The first regime encompasses low speed flow for which the heat transfer coefficients are determined from expressions appearing in standard heat transfer texts for flow over a flat plate. The second regime consists of a model for high speed flow in which the convective heat transfer coefficient is evaluated from an experimental correlation for flow over the upper surface of the shuttle orbiter vehicle (Ref. 9). The third section of the model encompasses a low to high speed transitional flow regime. Within this regime the heat transfer coefficient is an interpolated value that lies between the values obtained in the low and high speed regimes. Calculations for the convective heat flux for all three regimes are based on Eckerts reference enthalpy method (Ref. 10).

Within each of the three regimes the heat transfer coefficient is calculated for cases where the flow is laminar, transitional or fully turbulent. In addition to the evaluation of the heat flux when the flow is forced, the procedure accounts for heat transfer by free convection at times when the shuttle vehicle is stationary or moving with a relatively low velocity.

The program for the evaluation of the aerodynamic heating rate is divided into six sub-tasks each of which is written as a separate subprogram. This procedure allows for changes in the periphery of the program without affecting the program foundation. The basic calculations are carried out in and controlled from the SUBRØUTINE CØNVEC. Atmospheric temperature and speed of sound are evaluated within the SUBRØUTINE ATMØS. Atmospheric properties evaluated at the reference temperature are calculated within the SUBRØUTINE REFP. The orbiter velocity and altitude are evaluated in the FUNCTIØN subprograms VELSH and ALTSH, respectively. The SUBRØUTINE NUS evaluates the Nusselt number for the radiator system.

It should be noted that the analysis does not account for the effects of shock wave interaction or interference heating caused by flow interference between the orbiter, booster or any supporting structure.

The analysis for the determination of the aerodynamic heating first requires the evaluation of a reference temperature which is used for the determination of all air properties. The reference temperature is a function of the Prandtl number and recovery factor of the air, as well as the vehicle Mach number.

The Mach number in turn is a function of the altitude and velocity of the orbiter at any instant time. Altitude and velocity profiles for the orbiter are contained in data arrays supplied by the user (see Part I, Chapter B). If the value of the integer I is used to specify either ascent or reentry phase, then the N paired data points which define the velocity V and elevation Z as a function of time t may be expressed functionally as

$$V_i = V_i\ (I,\ t_i) \quad i = 1,2,\ldots,N \tag{7.1}$$

$$Z_i = Z_i\ (I,\ t_i) \quad i = 1,2,\ldots,N \tag{7.2}$$

Once the orbiter velocity and altitude are known as a function of time, the vehicle Mach number M may be calculated from the equation

$$M = \frac{V}{c} \tag{7.3}$$

The speed of sound c is an atmospheric property that is a function only of the altitude.

The reference temperature is a function of the recovery factor r which for laminar flow is

$$r = \sqrt{N_{Pr}}$$

and for turbulent flow (Ref. 11) is

$$r = N_{Pr}^{\,(8 + 0.528M^2/(22 + M^2))} \qquad (7.4)$$

where the Prandtl number N_{Pr} is an atmospheric property. To avoid a discontinuity in the value of the recovery factor between the laminar and turbulent flow models, Eq. 7.4 was used as the expression for the recovery factor for both flow models. The resulting error in the reference temperature was found to be approximately 5 R in an extreme case.

All of the properties for the atmosphere used in the evaluation of the heat transfer coefficient are evaluated at the high speed reference temperature. Eckert (Ref. 10) recommends the expression

$$i^* = 0.5\ (i_\infty + i_w) + 0.11\ r\ (\gamma - 1)\ M^2 i_\infty \qquad (7.5)$$

for the reference enthalpy i^* which can be converted to the reference temperature T^* once the relationship

$$T^* = T^*\ (i^*) \qquad (7.6)$$

between the atmospheric enthalpy and temperature is known. The subscripts "∞" and "w" in Eq. 7.5 refer to the enthalpy of the air evaluated at the free stream and surface temperature, respectively, and γ is the ratio of the specific heats for air.

It should be mentioned that when velocities are low ($M \rightarrow 0$) Eqs. 7.5 and 6 yield a reference temperature that approaches the film temperature $(T_\infty + T_w)/2$. As a result Eqs. 7.5 and 6 were used to evaluate the reference temperature for all three flow regimes, i.e., low speed, high speed and the transitional regimes.

The convective flux is the product of the convective heat transfer coefficient and the difference between the air enthalpy evaluated at the surface temperature and at the adiabatic wall temperature. The adiabatic wall enthalpy i_{aw} is related to the free stream enthalpy, recovery factor and vehicle velocity by the relationship

$$i_{aw} = i_\infty + \frac{rV^2}{2g_c} \tag{7.7}$$

The convective heat transfer coefficient h_i used in the reference enthalpy method may be expressed in terms of the Nusselt number N_{Nu}

$$N_{Nu} = \frac{h_i x c_p^*}{k^*} \tag{7.8}$$

where c_p^* and k^* denote the atmospheric specific heat and thermal conductivity evaluated at the reference temperature T^*. The symbol x denotes a characteristic length of the radiator system which for forced convection is the distance from the stagnation point on the shuttle to the center of the radiator panel.

The expressions for the orbiter Nusselt number selected for the low speed and high speed regime and for laminar, transitional and turbulent flow are summarized in Table 2. Values for the Nusselt number for conditions lying between the low and high speed regimes were obtained by interpolation so that the convective heat flux from the shuttle varies

TABLE 2

FORCED CONVECTION NUSSELT NUMBER FOR ORBITER

	LOW SPEED REGIME $M \leq 0.5$	HIGH SPEED REGIME $M \geq 1.0$
LAMINAR FLOW $Re < 1.0x10^5$	$N_{Nu} = 0.332\ N_{Re}^{1/2} N_{Pr}^{1/3}$	$N_{Nu} = 0.375\ N_{Re}^{0.514}\ N_{Pr}$
TRANSITIONAL FLOW $1x10^5 \leq Re \leq 1x10^6$	$N_{Nu} = 6.78x10^{-5} N_{Re}^{1.238} N_{Pr}^{1/3}$	$N_{Nu} = 3.39x10^{-4}\ N_{Re}^{1.111}\ N_{Pr}$
TURBULENT FLOW $Re > 1x10^6$	$N_{Nu} = 0.0288\ N_{Re}^{0.8} N_{Pr}^{1/3}$	$N_{Nu} = 0.0346\ N_{Re}^{0.7746}\ N_{Pr}$

continually from one regime to the other. The symbols N_{Re} and N_{Nu} appearing in the table denote the Reynolds number and Prandtl number, respectively, where

$$N_{Re} = \frac{\rho^* V x}{\mu^*}$$

$$N_{Pr} = \frac{\mu^* c_p^*}{k^*}$$

The "*" superscript on each property indicates that the property is evaluated at the temperature T*.

For the low speed regime the expressions for the Nusselt number are those for laminar transitional and turbulent flow over a flat plate (Ref.6*) Nusselt number relationships for high speed flow regime are taken from Ref. 9 where experimental wind tunnel data are presented for a delta space shuttle orbiter. The data are for leeward surface heat transfer at angles of attack between 10° and 30° and Mach numbers of 8 and 16. The Nusselt number is shown to be relatively independent of angle of attack so that the high speed correlation may be applied to both the ascent phase for which the angle of attack is approximately zero and the reentry phase when the angle of attack may approach 60°. The scatter in the data of Ref. 9 from the selected Nusselt relationships is on the order of 100%.

The leeward surface correlation was selected because the aerodynamic heating rates in this region of the shuttle are relatively low when compared to heating rates for the lower body or windward surface. Estimates place the peak reentry temperature of the lower surface stagnation line

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* pp 296 and 313

around 2100 F while the peak leeward temperature is estimated to be about 600 F (Ref. 12). Therefore placing the radiator on the upper surface of the orbiter not only will result in a more efficient operation upon reentry, by also will minimize the need for reservicing of the surface coating on the radiator panels.

The aerodynamic heating analysis includes free convection from the radiator surface during pre-launch operation and when the shuttle vehicle is moving with a relatively low velocity. The expression for the free convection Nusselt number is a function of the Grashof Prandtl product where the Grashof number N_{Gr} is given by

$$N_{Gr} = g\beta \left(\frac{\rho}{\mu}\right)^2 y^3 (T_w - T_\infty)$$

where g represents the acceleration of gravity, ρ, u and T_∞ are the atmospheric density, dynamic viscosity and temperature, respectively and T denotes the radiator surface temperature. The symbol y denotes the overall dimension of the radiator panel in the direction parallel to the acceleration of gravity. Since the atmosphere is assumed to be an ideal gas, the coefficient of thermal expansion β is simply the reciprocal of the average absolute temperature of the air

$$\beta = \frac{1}{T_w + T_\infty}$$

The free convection Nusselt numbers N_{Nu_f} and their applicable ranges of Grashof Prandtl product used for this analysis are

$$N_{Nu_f} = 1.585 \, (N_{Gr}N_{Pr})^{0.195} \qquad (10^{-1} < N_{Gr}N_{Pr} < 10^9) \qquad (7.9a)$$

$$N_{Nu_f} = 0.590\ (N_{Gr}N_{Pr})^{0.250} \qquad (10^4 \leq N_{Gr}N_{Pr} \leq 10^9) \tag{7.9b}$$

$$N_{Nu_f} = 0.130\ (N_{Gr}N_{Pr})^{0.333} \qquad (N_{Gr}N_{Pr} > 10^9) \tag{7.9c}$$

The values for the free convection Nusselt number given in Eqs. 7.9 were multiplied by the ratio (x/y) and then added to the forced convection Nusselt number to obtain a value that accounts for combined free and forced convection in the low speed regime.

Equations 7.1 through 7.8 combined with the appropriate Nusselt number relationship from Table 2 for forced convection and Eqs. 7.9 for free convection are sufficient to determine the convective heat flux into the radiator surface which is given by

$$q''_{aero} = h_i\ (i_\infty - i_{aw}) \tag{7.10}$$

The convective flux may be normalized by dividing by the heat flux σT_o^4 or

$$\tilde{q}_{aero} = \frac{h_i\ (i_\infty - i_{aw})}{\sigma T_o^4} \tag{7.11}$$

where T_o is the fluid temperature at the inlet plane to the flow channel. The normalized convective heat flux given by Eq. 7.11 is used in the energy equation for both the fin (Eq. 2.18) and the meteoroid protection layer (Eq. 5.5).

B. DESIGN PARAMETERS

Certain design parameters are necessary for the design specification, for the selection of the optimum radiator system and even the system definition as required for the heat transfer analysis. In the following are discussed, in that order, the prediction of the meteoroid protection layer thickness, the system weight and a collection of nondimensional groups which define the radiator system, the operational conditions, and the performance characteristics.

8. Meteoroid Protection Thickness

In this section an engineering equation is developed to predict the thickness of a meteoroid protection layer required to cover all radiator surfaces that might be damaged by the impact of a meteoroid. Several assumptions have been made during the derivation. They are:

1. The meteoroid particle is spherical.
2. The meteoroid flux is isotropic.
3. Poissons distribution law describes the probability of an impact of a meteoroid.

It should be mentioned that any equation used to predict meteoroid protection thickness is only as accurate as the experimental data used in that equation. Even though much information has been published in recent years concerning protection theories, there is still considerable question as to the density, velocity and mass distribution of meteoroid particles in outer space. In addition to these uncertainties, two basic models for penetration theory have been proposed within the last decade and there appears to be no close agreement between the two. Experimental verification of either model has been hampered by the fact that particle velocities used in experimental tests have only recently approached the meteoroid velocity range. In short, an extremely reliable theory for the prediction of protection layer thickness does not presently exist.

Structural materials that can be used in this study as a protection layer are copper, aluminum and beryllium. While both copper and aluminum were selected primarily as fin and tube materials due to their superior heat transfer characteristics, beryllium was chosen for its protection capabilities. The penetration theory predicts a protection layer thickness that decreases as the modulus of elasticity increases. Therefore beryllium becomes an attractive protection material due to its high modulus of elasticity and its relatively low density. In fact studies (Ref. 13 and 14) have shown that beryllium can significantly reduce protection layer weight.

The basic equation (Ref. 15) for the depth of penetration of a meteoroid particle into a target of infinite depth is

$$P_\infty = \gamma \, d \left(\frac{\rho_p}{\rho_t}\right)^{\phi} \left(\frac{\overline{V}}{\overline{c}}\right)^{\theta} \tag{8.1}$$

where

- γ empirical constant generally accepted to be in the range of 1.5 to 2.5.
- ρ_p density of the meteoroid particle
- ρ_t density of the target material
- $\overline{V}$ velocity of the meteoroid particle
- $\overline{c}$ velocity of sound in the target material
- d diameter of the meteoroid particle
- ϕ constant between 1/3 and 2/3
- θ constant between 1/3 and 2/3

The ratio of the meteoroid velocity and the velocity of sound in the target represents a target Mach number. The velocity of sound in the target can be expressed in terms of the modulus of elasticity

$$\overline{c} = \sqrt{E_t g_c / \rho_t} \tag{8.2}$$

where

E_t modulus of elasticity of the target material

g_c proportionality constant relating mass units to force units

ρ_t target density

If the meteoroid particle is assumed to be spherical, the diameter may be written in terms of its mass

$$d = \left(\frac{6M_p}{\pi\rho_p}\right)^{1/3} \tag{8.3}$$

where

M_p meteoroid mass

ρ_p meteoroid density

The probability that an exposed surface will be struck by a meteoroid during a period of time can only be determined after the distribution of meteoroids of a given mass is known. This information is usually given in the form of an equation such as

$$F = \alpha M_p^{-\beta} \tag{8.4}$$

where

F cumulative number of impacts of particles with mass M or larger per unit area per unit time

M_p mass of the meteoroid particle

The symbols α and β reprsent experimentally determined constants. Published (Ref. 16) values of α and β vary over a considerable range, but they lie within the limiting values,

$$1.3 \times 10^{-15} < \alpha < 2.54 \times 10^{-9} \qquad [ft^2 \text{ day } gm^{-\beta}]^{-1}$$

$$1.11 < \beta < 1.34 \qquad [\text{Dimensionless}]$$

The cumulative number of impacts on a surface with a vulnerable area of A during a mission time of τ by a meteoroid of mass M_p of larger is then

$$N = FA\tau = A\tau\ \alpha\ M_p^{-\beta}$$

It is generally assumed (Ref. 17) that meteoroids are randomly distributed in outer space and that each collision can be described by Poissons probability law. From the Poisson distribution function, the probability of zero events occurring P_o when the average number of events is N is

$$P_o = e^{-N}$$

or

$$\ln P_o = -N$$

Substituting the value for N gives the probability that no meteoroid of mass M or larger will impact on the surface of area A during time τ of

$$\ln P_o = A\tau\alpha\ M_\rho^{-\beta}$$

or

$$M_p = \frac{\alpha A\tau}{-\ln P_o}^{1/\beta} \tag{8.5}$$

To account for the fact that all meteoroids do not strike the protection layer normally, the meteroid velocity $\bar{V}$ may be replaced by a critical velocity $\bar{V}_c$ where

$$\bar{V}_c = \bar{V}(\cos\lambda)^n \tag{8.6}$$

λ angle between the direction of $\bar{V}$ and the normal to the protection surface n an experimentally determined constant

If n is selected to be unity the damage to the protection layer caused by an oblique collision is based on the meteoroid's normal component of velocity. A more conservative approach would be to set n = 0 in which case all particles are considered to impact normally.

If the meteoroid flux is assumed to be isotropic the angle dependence may be replaced by

$$(\cos\lambda)^n = \left(\frac{2}{3n\theta\beta+2}\right)^{1/3\beta} \tag{8.7}$$

Finally account must be taken for the fact that the meteoroid will not impact on an infinite target, but one with a finite thickness. As a result even though the meteoroid may not penetrate the protection layer, spalling may damage the radiator panel. To account for spalling the thickness of meteoroid protection t used should be larger than the predicted penetration into an infinite target or

$$t = aP_\infty \tag{8.8}$$

Accepted values of a lie between 1.5 and 2.0

Equations 8.1 through 8.7 may now be substituted into Eq. 8.8 to give an expression for the meteoroid protection layer thickness. The result is

$$t = a\gamma\left(\frac{6}{\pi}\right)^{1/3}\left(\frac{\alpha A\tau}{-\ln P_o}\right)^{1/3\beta}\rho_p^{-1/3}\left(\frac{\rho_p}{\rho_t}\right)^{\phi}\left(\frac{V}{12(E_t g_c/\rho_t)^{1/2}}\right)^{\theta}\left(\frac{2}{3n\theta\beta+2}\right)^{1/3\beta} \tag{8.9}$$

where

t - thickness of protection layer (inches)

a - experimental constant (dimensionless)

γ - experimental constant (dimensionless)

α - experimental constant that relates meteoroid flux to mass (gm/(day ft^2))

β - experimental constant that relates meteoroid flux to mass (dimensionless)

A - vulerable area requiring protection (ft^2)

τ - mission time (days)

P_o - probability of no damage caused by impact of meteoroid (dimensionless)

ρ_p - density of meteoroid particle (gm/cm^3)

ρ_t - density of protection layer (lb$_m$/ft^3)

$\bar{V}$ - velocity of meteoroid (ft/sec)

E_t - modulus of elasticity of protection material (lb$_f$/in^2)

g - 32.174 lb$_m$ft/lb$_f$sec^2

θ - experimental constant (dimensionless)

ϕ - experimental constant (dimensionless)

n - experimental constant that describes penetration depth as a function of angle of incident (dimensionless)

Selection of Values for Experimental Constants

Values for the experimental constant ρ, β, ρ_p and $\bar{V}$ used in Eq. 8.9 were selected from the Manned Spacecraft Center publication for meteoroid environment criterion (Ref. 18) .

The values for α and β for meteoroids having a mass between 1 gm 10^{-6} gm used in Eq. 8.4 are

$$\alpha = 1.888 \times 10^{-10} \quad gm^{\beta}/(ft^2 day) \tag{8.10}$$

$$\beta = 1.213 \tag{8.11}$$

The average meteoroid density is

$$\rho_p = 0.5 \text{ gm/cm}^3 \tag{8.12}$$

and the average meteoroid velocity is

$$\bar{V} = 20 \text{ km/sec.} \tag{8.13}$$

Values chosen for the remaining constants appearing in Eq. 8.9 are summarized in Table 3. Values of these constants are also listed in the table that will yield optimistic (minimum) and pessimistic (maximum) thicknesses for the meteoroid protection layer.

	Recommended Value	Pessimistic Value	Optimistic Value
a	1.75	2.0	1.5
γ	1.50	2.5	1.5
ϕ	1/2	1/3	2/3
θ	2/3	2/3	1/3
n	1.0	0	1.0

TABLE 3. Empirical Constants for Meteoroid Protection Layer Thickness

The following is an analysis of the sensitivity that the meteoroid protection layer thickness has to the uncertainty in the values of the five parameters listed in Table 3. This information will enable the user to judge his selection of these constants from within the recommended ranges.

An expression for the error in the meteoroid protection thickness may be obtained by taking the logarithm of Eq. 8.9 followed by differenting the resulting equation. This process yields the equation

$$\frac{dt}{t} = \frac{da}{a} + \frac{d\gamma}{\gamma} + \phi\left(\frac{\rho_p}{\rho_t}\right)\frac{d\phi}{\phi} + [\theta \ln\left(\frac{V}{c}\right) - \frac{n\theta}{3n\theta\beta+2}]\frac{d\theta}{\theta} - [\frac{n\theta}{3n\theta\beta+2}]\frac{dn}{n} \qquad (8.14)$$

If the symbol E_a is selected to represent the relative error in the meteoroid protection thickness resulting from a relative uncertainty in the value for the parameter a then it is evident from Eq. 8.14 that

$$E_a = \frac{dt/t}{da/a} = 1.0$$

when all other parameters are held constant. Similarly the error caused by an uncertainity in the value of γ will be

$$E\gamma = \frac{dt/t}{d\gamma/\gamma} = 1.0$$

When the value for θ is taken to be the recommended value of 2/3 and β is set equal to the value fixed by MSC's environmental model (Eq. 8.11), the resulting error in the meteoroid protection layer thickness due to an uncertainity in the value for n is

$$E_n = \frac{dt/t}{dn/n} = -\left(\frac{n\theta}{3n\theta\beta+2}\right) = -0.15$$

The magnitude of the error for the final two parameters ϕ and θ are a function of the material selected for the protection layer. In order to give an indication of the range of errors that can be expected for various protection materials, the errors were calculated for the three structural materials that were selected in the program: aluminum, beryllium and copper. If the meteoroid particle density is assumed to be fixed at the value recommended by the MSC environmental model (Eq. 8.12), then an uncertainty in the value of ϕ from the recommended value of 1/2 would cause an error in the protection thickness of

$$E_\phi = \frac{dt/t}{d\phi/\phi} = \phi \ln\left(\frac{\rho_p}{\rho_t}\right)$$

which for each of the three structural materials results in the following errors

$$E_\phi = -0.85 \qquad \text{aluminum}$$

$$E_\phi = -0.65 \qquad \text{beryllium}$$

$$E_\phi = -1.44 \qquad \text{copper}$$

The high density and low modulus of elasticity of copper makes its protection characteristics rather undesirable. For this reason the error of 1.44 indicated for copper probably will never be experienced in practice, and this value should be considered as a limiting case.

An uncertainty in the value of θ from the recommended value of 2/3 would cause an error in the protection layer thickness equal to

$$E_\theta = \frac{dt/t}{d\theta/\theta} = [\theta \ln (\frac{\bar{V}}{\bar{c}}) - \frac{n\theta}{3n\theta\beta+2}]$$

which for each of the three structural materials is

$E_\theta = 0.77$ aluminum

$E_\theta = 0.20$ beryllium

$E_\theta = 1.01$ copper

The errors calculated in the analysis are summarized in Table 4

TABLE 4 Ratio of Relative Error in Thickness To Relative Uncertainty in Empirical Constants

Protection Material / Parameter	Aluminum	Beryllium	Copper
a	1.0	1.0	1.0
γ	1.0	1.0	1.0
ϕ	- 0.85	- 0.65	- 1.44
θ	0.77	0.20	1.01
n	- 0.15	- 0.15	- 0.15

If the error values for copper are excluded, the protection thickness is most sensitive to variations in the parameters a and γ and least sensitive to variations in the parameter n. Even though the protection thickness is least sensitive to the selection of n, it should be noted that the 100% variation between the optimistic and pessimistic value of n is the largest of all of the parameters. Also it should be noted that the signs on the values in Table 4 indicate that an increase in the parameters a, γ and θ result in an increase in the protection layer thickness, while an increase in the values for ϕ and n result in a decrease in the protection layer thickness. This fact can be verified by the choice of the values of each of the parameters listed in Table 3. The values labeled as those which will produce a pessimistic value for the protection thickness are maximum values for a, γ and θ and minimum values for ϕ and n.

To further evaluate the effect the meteoroid protection thickness has on the performance of the fin system, the temperature of the coolant fluid at the exit plane of the flow channel was evaluated first under the "pessimistic" conditions for the meteoroid protection layer, second for the "recommended' conditions and finally for the "optimistic" conditions. The results of these computer runs are shown below.

Case	Protection Layer Thickness-inches	Normalized Outlet Fluid Temperature T/T_o
Pessimistic	0.377	0.8855
Recommended	0.063	0.8922
Optimistic	0.020	0.8932

Even though the thickness of the meteoroid protection layer varies by nearly a factor of 20, the resulting error in the enthalpy drop is only

$$\frac{0.8932 - 0.8855}{1 - 0.8922} \cdot 100\% = 7.15\%$$

9. The Mass of the System

The system mass is computed, firstly as a convenience for the user and secondly for the purpose of the planned system optimization. The system mass includes

(i) the mass of the fluid in all tubes

$$M_c = n_t \frac{d^2\pi}{4} \int_o^L \rho_c dz = n_t \rho_{c,o} \frac{d^2\pi}{4} L \int_o^1 \nu d\zeta \qquad (9.1)$$

(ii) the mass of the fins

$$M_f = n_t H L \rho_f (s_r + s_t) \qquad (9.2)$$

(iii) the mass of all tubes

$$M_w = n_t s_w L \cdot \pi (d + s_w) \rho_w \qquad (9.3)$$

and

(iv) the mass of the protection layer

$$M_m = n_t s_m L \rho_m [\pi(d + s_w + s_m) - s_r] \qquad (9.4)$$

but it does not include the thermal coating nor the mass of the manifold and the fluid in the manifold. In Eqs. 9.1 through 4 represent

n_t	the number of tubes
d	the tube diameter
ρ	the density
L	the tube length
H	the fin height, distance between fin root and fin tip
s	the thickness

while the subcripts designate ρ and s as follows

c	coolant fluid
f	fin
m	meteoroid protection layer
r	fin root
t	fin tip
w	tube wall
o	inlet condition.

The integral in Eq. 9.1 is time-dependent and evaluated at the initial conditions.

10. Nondimensional System Parameters

The governing equations in the preceding radiator system analysis are developed in non-dimensional form for the purpose of (i) reducing the number of parameters, (ii) evolving the set of relevant parameters, and (iii) presenting the results in a general form which is applicable to groups of systems rather than an individual system. Although these tasks are planned for the second contract phase a summary of parameters is presented here, first for the detailed analysis discussed in the preceding chapters and then for the simplified analysis presented in Appendix C.

The transient flow field in the coolant channel and the temperature field over the fin can be represented as functions of:

a) the independent variables

time $$\tau = \frac{tw_o}{L} \tag{10.1}$$

axial coordinate $$\zeta = \frac{z}{L} \tag{10.2}$$

radial coordinate $$\eta = \frac{2r}{d} \tag{10.3}$$

transverse coordinate normal to the channel axis $$\xi = \frac{x}{H}$$

b) <u>the dependent system variables</u>

fin temperature $\theta_f\ (\xi,\zeta;\tau) = \frac{T_f}{T_o}$ (10.4)

channel temperature $\theta_w\ (\eta,\zeta;\tau) = \frac{T_w}{T_o}$ (10.5)

meteroid protection
layer temperature $\theta_m\ (\eta,\zeta;\tau) = \frac{T_m}{T_o}$ (10.6)

coolant fluid temperature $\theta_c\ (\zeta;\tau) = \frac{T_c}{T_o}$ (10.7)

coolant fluid pressure $\pi(\zeta,\tau) = \frac{p}{p_o}$ (10.8)

coolant fluid velocity $\omega(\zeta;\tau) = \frac{w}{w_o}$ (10.9)

The solution to the problem will depend on the geometery of the system, the material properties and the definition of operational conditions. There was no attempt made to establish similitude with respect to the material properties because the scaling laws would either be too restrictive to allow for general property variations or too complex (for instance, the concept of corresponding states for gases). Consequently, the ϕ - parameters defined in Eqs. 3.27 through 3.30, in Eq. 4.4 and in Eqs. 5.1, 2 and 6 are omitted from this summary; they constitute temperature and pressure variation of properties. This leaves the following list of parameters, in additon to n, the number of tubes:

c) the geometric parameters

fin height-to-length ratio $\bar{H} = \frac{H}{L}$ (10.10)

fin profile slope $c = \frac{s_r - s_t}{2H}$ (10.11)

fin root thickness $\bar{s}_r = \frac{s_r}{H}$ (10.12)

tube diameter-to-length ratio $\delta = \frac{d}{L}$ (10.13)

channel wall thickness $\bar{s}_w = \frac{2s_w}{d}$ (10.14)

protection layer thickness $\bar{s}_m = \frac{2s_m}{d}$ (10.15)

d) the operational parameters

coolant flow Reynolds number $N_{Re} = \frac{dw_o}{\nu_o}$ (10.16)

Prandtl number (representing coolant selection) $N_{Pr} = (\frac{\mu c_p}{k_c})_o$ (10.17)

inlet pressure heat $F_p = (\frac{p}{\rho w})_o$ (10.18)

compressibility $\bar{Q}_o = \frac{\pi n \rho d^2 c_p}{4\sigma T_o^3}$ (10.19)

inlet coolant power flux $F_z = \left(\frac{p}{\rho c_p T}\right)_o$ (10.20) where n is the number of tubes

incident radiant heat flux $$\bar{Q}_{rad} = \frac{\alpha_o q''}{\varepsilon_o \sigma T_o^4} \quad (10.21)$$

meteoroid velocity $$M_m = \frac{v_m}{c_m} \quad (10.22)$$

protection layer density
(representing selection of
protection layer material) $$\phi_\rho = \frac{\rho_{mt}}{\rho_m} \quad (10.23)$$

where ρ_{mt} is the density of the meteoroids.

Similarity for ascent and reentry operations is difficult to establish unless one restricts oneself to similar velocity-altitude profiles which can be represented by the

max. Mach number $$M_{max} = (v/c)_{max} \quad (10.24)$$

and its corresponding (through same altitude)

Reynolds number $$(N_{Re})_\infty = \frac{\rho_\infty v L}{\mu_\infty} \quad (10.25)$$

Prandtl number $$(N_{Pr})_\infty = \frac{\mu_\infty c_{p\infty}}{k_\infty} \quad (10.26)$$

Grashof number
(before launch) $$N_{Gr} = \frac{g L^3 \beta \Delta T}{\nu^2}$$

This completes the list of non-dimensional groups resulting from the detailed analysis. The simplified, steady-state analysis involves only ten parameters which govern the solution. The reader is referred to Appendix D for details. There are two operational parameters,

(i) the characteristic length

$$L_o = \dot{M}\, c_p/(\varepsilon\sigma T_o^3) \tag{10.27}$$

where $\dot{M} = n\rho_c w_o \frac{d^2\pi}{4}$ stands for the total mass flux.

(ii)

$$\Phi = \varepsilon\sigma T_o^3 \dot{M}\, c_p/k_c^2 \tag{10.28}$$

and five geometrical parameters, namely L*, H*, d* and n, where all starred quantities are obtained by dividing the unstarred quantities by L_o of Eq. 10.27. The fluid property is represented by two groups, the Prandtl number and the ratio k_f/k_c of thermal conductivities.

Finally, the system mass is defined through the above nine parameters and the mass augmentation factor F, that is the mass of tube, fluid and protection layer divided by the fin panel mass

$$F = \pi\left[\frac{\rho_w}{\rho_f}\;\frac{d_m}{d}\;\frac{s_w}{d}\;\left(1 + \frac{\rho_m}{\rho_f}\;\frac{A_m}{A_w}\right) + \frac{\rho_c}{4\rho_f}\right] \tag{10.29}$$

where $d_m = d + S_w$

A cross-section, with subscripts as defined before.

C. Properties

The fundamental principles used to prepare the required thermophysical properties for inclusion into the computer code are exhibited in this chapter while the specific details concerning the materials treated in this program phase are placed into the appendices.

The principles involved are those of macroscopic thermodynamics treated in most elementary texts. The approach of deriving analytic expressions for the required properties is not unique because the starting point is dictated by the availability of experimental data. The result, however, must be of the same form regardless of whether, for instance, the coolant fluid is gaseous or liquid.

The properties of the structural materials are the least problematic ones since they depend on the temperature at most; and the standard polynomial collocation methods are entirely sufficient. Care must be exercised, however, that the collocation imply continuous fourth derivatives for highest integration efficiency or, less desirable, at least continuous representation of the property itself which may exclude piecewise allocation of degrees higher than one.

What is said about the properties of structural materials holds in principle for the description of the atmosphere whose properties depend only on altitude. Even though the optical properties of the thermal coating depend, in general, on wave-length and temperature, the spectral dependence is integrated into the averaged ("gray") properteis (see Eqs. 6.5 and 6), and the results are functions of one variable, the temperature. Consequently, there remains but the discussion of the coolant fluid properties which depend strictly on two state variables.

In macroscopic thermodynamics there are required two equations of state for the description of a substance, namely the thermal equation of state $f(\rho,p,T) = 0$ which relates any one of density ρ, pressure p and temperature T to the remaining two, and the caloric equation of state, perhaps in the form of $c_v^o = f(T)$ where c_v^o is the zero-pressure specific heat at constant volume. These two equations are sufficient to develop all of the required thermodynamic functions, namely:

(i) specific heat at constant pressure $c_p(\rho,T)$

(ii) isobaric thermal expansion coefficient $\beta(\rho,T)$

(iii) isothermal bulk modulus $\kappa(p,T)$

(iv) enthalpy $h(\rho,T)$

These functions are discussed in Section 11.

The transport properties, namely the thermal conductivity $k(\rho,T)$ and the dynamic viscosity $\mu(\rho,T)$ are correlated on the basis of residuals as explained in Section 12. The properties of the atmosphere are dealt with in Section 13.

11. Thermodynamic Properties

The first step in developing thermodynamic properties is to secure a thermal equation of state

$$f(p,\rho,T) = 0 \tag{11.1}$$

For almost all pure gases and air, this equation can be found in the literature, either in the form suggested by Benedict-Webb-Rubin (virial expansion) or in that suggested by Beattie-Bridgeman. Both equations are explicit in p,

$$p = p(\rho,T) \tag{11.2}$$

so that κ is immediately obtained from Eq. 11.2 by implicit differentiation

$$\kappa(\rho,T) = \frac{1}{\rho}\left(\frac{\partial\rho}{\partial p}\right)_T \tag{11.3}$$

which can be evaluated as $\kappa(p,T)$ after inversion of Eq. (11.2) into

$$\rho = \rho(p,T) \tag{11.4}$$

The inversion of Eq. 11.2 is facilitated by computing $(\partial p/\partial\rho)_T$ from Eq. 11.2 and subsequently applying the Newton-Raphson method along the specified isotherm with temperature T in Eq. 11.4.

The isobaric thermal expansion coefficient

$$\beta = -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_p$$

is also obtained by implicit differenciation of Eq. 11.2 while keeping the left-hand side constant.

After having collocated the zero-pressure specific heat at constant volume that is c_v^o (T) by a power polynomial in T, one obtains first the specific heat at constant volume

$$c_v(\rho,T) = c_v^o(T) - T \int_0^{\rho} \left(\frac{\partial^2 p}{\partial T^2}\right)_{\rho} \frac{d\rho'}{(\rho')^2} \qquad (11.5)$$

and then the specific heat at constant pressure

$$c_p(\rho,T) = c_v(\rho,T) + \frac{T\beta^2}{\rho\kappa} \qquad (11.6)$$

The derivative in Eq. 11.5 is obtained form Eq. 11.2; and β and κ are both function of ρ or p and T.

Finally the enthalpy h is calculated from its definition

$$h\ (\rho,\ T) = \frac{p}{\rho} + u\ (\rho,\ T) \qquad (11.7)$$

where the internal energy u may be obtained by two successive integrations, the first one along an isotherm (over ρ), and the second one along an isochore (over T):

$$u = u(\rho_o,T_o) + \int_{T_o}^{T}\int_{\rho_o}^{\rho} c_v(\rho',T')d\ 'dT' + \int_{\rho_o}^{\rho}[p - \frac{T\beta}{\kappa}]\ \frac{d\rho'}{(\rho')^2} \qquad (11.8)$$

Liquids can be treated, in principle, as gases; except that the equation of state, Eq. 11.1, is rarely available. One may find, with little difficulty the zero-pressure isobaric expansion coefficient $\beta_o = c(T)$, and then represent adequately the isothermal bulk modulus by

$$\kappa(p,T) = a(T) + b(T)\ p \qquad (11.9)$$

Under any circumstances, one must satisfy

$$\left(\frac{\partial\beta}{\partial p}\right)_T + \left(\frac{\partial\kappa}{\partial T}\right)_p = 0 \qquad (11.10)$$

which yields, form Eq. 11.9

$$\beta(p,T) = -a'p - \frac{b'}{2}\ p^2 + c \qquad (11.11)$$

where primes indicate differentiation with respect to T, of the polynomials a(T) and b(T) in Eq. 11.9. Equations 11.9 and 11 yield for the density

$$\rho(pT) = \rho(0,T_o)e^{[a(T)p + \frac{1}{2}b(T)p^2 - \int_{T_o}^{T} c(T')dT']} \qquad (11.12)$$

The specific heats and the enthalpy are to be derived as for gases (see Eqs. 11.6 and 7). Other possibilities are to develop κ from the speed of sound and the ratio of specific heats; but the reader is warned not to imply $\kappa = 0$ or $c_p = c_v$, unless there is sufficient evidence to support these assumptions.

12. Transport Properties

While the thermal conductivity k and the dynamic viscosity μ of liquids may often times be adequately represented by functions of temperature T alone (facilitated by polynomial collocation), these same properties for gases depend on density as well. It is recognized that the difference, or residue

$$\psi_1(\rho) = k(\rho,T) - k^*(T) \tag{12.1}$$

between the thermal conductivity $k(\rho,T)$ and the low-pressure thermal conductivity $k^*(T)$ depends only on the density. Similarly, for the dynamic viscosity

$$\psi_2(\rho) = \mu(\rho,T) - \mu^*(T) \ . \tag{12.2}$$

Hence k and μ can be represented by the sum of two polynomials, one in ρ and the other in T. The residuals ψ_1 and ψ_2 are published for a number of gases or may be developed from property data (Ref. 19 for N_2 and He)

13. Atmospheric Properties

For the prediction of aerodynamic heat fluxes incident on the radiator system during ascent and reentry (see Sect. 7) the evaluation of the following atmospheric properties are required:

Temperature

Pressure

Density

Molecular Weight

Speed of Sound

Viscosity

Thermal Conductivity

Specific Heat at Constant Pressure

Enthalpy

The model for these atmospheric properties is presented in two sections. The first covers altitudes from sea-level to 301,000 feet. Within this range the molecular weight is assumed to be constant and the temperature variation with altitude is a sequence of connected line segments. The second section of the model covers altitudes above 301,000 feet where the molecular weight decreases linearly with altitude. For this altitude range the approximate polynomial expressions for density and pressure suggested in Part 4 of Ref. 20 were used. Errors between the values given by the approximate expression and the 1962 Standard Model are less than 5% over the entire range of altitudes.

Atmospheric air is assumed to be an ideal gas for all altitudes. Therefore compressibility effects at low altitudes are neglected. The error in computed densities resulting from the ideal gas assumption may be as high as 0.05% for altitudes below 6 miles, but becomes less than 0.01% above 12 miles (Ref. 20). The air is also assumed to be in hydrostatic equilibrium.

All properties except geopotential altitude, specific heat and enthalpy are evaluated from expressions presented in Refs. 20 and 21. The expression for geopotential altitude was taken from Ref. 22, while specific heat and enthalpy data were taken from Ref. 23.

The model developed for the atmospheric properties is considered to be applied to altitudes up to 100 miles and to latitudes between 30 and 60°N. It is anticipated that atmospheric properties are not needed for altitudes exceeding 100 miles, because the convective heat flux from the fin system will be neglible at this altitude and above.

The properties for the earths atmosphere are known with increased uncertainty as the altitude increases. In fact the 1962 Standard Atmosphere (Ref. 21)consists of four regions as follows:

0 - 20 km	Standard
20 - 32 km	Proposed Standard
32 - 90 km	Tentative
90 - 700 km	Speculative

Any uncertainity in the atmospheric properties will naturally be reflected as an error in the convective heat flux from the shuttle vehicle. Fortunately during the ascent phase of the shuttle operation the convective flux from the radiator system is fairly small compared to the radiative flux by the time the shuttle has approached altitudes for which the atmospheric properties are considered to be "speculative"; on the other hand during re-entry, significant convective fluxes are known to exist at altitudes above 90km. As a result every effort should be made to revise the existing atmospheric property model at high altitudes as new data become available.

The atmospheric model is based on several primary constants. The sea-level pressure, temperature, molecular weight, density and acceleration of gravity and the universal gas constant were assigned the fixed values of

P_o = 2116.22 lbf/ft^2

T_o = 518.67 R

M_o = 28.9644

ρ_o = 0.07647 lbm/ft^3

g_o = 32.1741 ft/sec^2

R^* = 1545.31 ft lbf/lb mole R

13.1 Properties for Altitudes Less than 301,000 feet.

a. Geopotential Altitude - H

The state variables for air are expressed in terms of the single variable, the geopotential altitude

$$H = \int_0^Z \frac{g(z)}{g_o}\, dz =$$

$$Z - 1.573126 \times 10^{-7} Z^2 + 2.4656553 \times 10^{-14} Z^3$$
$$- 3.8667054 \times 10^{-21} Z^4 + 6.0621354 \times 10^{-28} Z^5$$
$$- 9.5013649 \times 10^{-35} Z^6 \qquad (13.1)$$

where Z is the geometric altitude in meters, g_o is the acceleration of gravity at sea-level and g(Z) denotes the local acceleration of gravity. See Ref. 22 for details.

b. Temperature - T

The general expression of the temperature as a function of geopotential altitude is

$$T = T_b + L(H - H_b) \qquad (13.2)$$

T_b and H_b are the endpoints of straight-line segments representing T(H) and are listed, together with L(H) in the following table.

H_b (km)	L (K/km)	T_b (K)
0		288.15
	- 6.5	
11		216.65
	0.0	
20		216.65
	1.0	
32		228.65
	2.8	
47		270.65
	0.0	
52		270.65
	-2.0	
61		252.65
	-4.0	
79		180.65
	0.0	
90		180.65

TABLE 5. Lapse Rate and Base Temperatures for Atmospheric Model

c. Molecular Weight - M

The molecular weight is constant at a value of 28.9644.

d. Pressure - P

Within a region where the temperature varies linearly, the ideal equation of state and the hydrostatic yield the following expressions for pressure:

$$\frac{P}{P_b} = \left[\frac{T_b}{T_b + L(H - H_b)} \right]^{\frac{g_o M_o}{R^* L}} \qquad (L \neq 0) \qquad (13.3)$$

$$\frac{P}{P_b} = \exp \left[- \frac{g_o M_o (H - H_b)}{R^* T_b} \right] \qquad (L = 0) \qquad (13.4)$$

i.e $11 \leq H \leq 20$ km
$47 \leq H \leq 52$ km
$79 \leq H \leq 90$ km

The subscripts "o" denotes a quantity evaluated at sea-level and the subscript "b" denotes a quantity evaluated at the base of one of the straight line segments of the atmospheric model.

c. Density - ρ

The density may be calculated from the ideal equation of state once the temperature and pressure have been evaluated.

$$\rho = \frac{MP}{R^* T} \qquad (13.5)$$

f. Speed of Sound - c

The speed of sound was evaluated from the expression

$$c = \left[\gamma \; \frac{R^{*}T}{M} \right]^{1/2} \tag{13.6}$$

For altitudes less than 301,000 feet the ratio of specific heats is taken to have a fixed value of 1.40

g. Viscosity - μ

The dynamic viscosity was evaluated from the expression

$$\mu = \frac{\beta T^{3/2}}{T + S} \tag{13.7}$$

where

$$\beta = 1.458 \times 10^{-6} \quad \frac{kg}{\sec\, m(K)^{1/2}}$$

and

$$S = 110.4\ K$$

h. Specific Heat at Constant Pressure c_p and Enthalpy i

Values for c_p and i between the temperatures of 100 R and 6400 R were taken from the standard Gas Tables (Ref. 23) and placed in the program in tabular form. A value of c_p and i at any temperature intermediate to a pair of tabular values was determined by an interpolation routine (see Section 17).

13.2 Properties for Altitudes Greater than 301,000 Feet

a. Pressure - P

The pressure for altitudes between 301,000 and 528,000 feet is based on the polynomial approximation given in Part IV of Ref. 20. The pressure is written in terms of the sea-level pressure P_o in the form

$$P = P_o \left\{ \sum_{n=0}^{11} [A_n Z^n]^{-4} \right\} \tag{13.8}$$

where Z is the geometric altitude and values for A_n appear in Table 4.1 of Ref. 20.

b. Density - ρ

The density is written in terms of a similar polynomial

$$\rho = \rho_o \left\{ \sum_{n=0}^{11} [B_n Z^n]^{-4} \right\} \tag{13.9}$$

where values of B_n appear in Table 4.1 of Ref. 20.

c. Molecular Weight - M

The molecular weight is assumed to vary linearly with altitude Z (see Fig. I.2.7 in Ref. 21). The resulting expression for M is

$$M = 28.9644 - 0.030949\ (Z - 90)$$

where Z is in km.

d. Temperature - T

The temperature is calculated from the values for pressure, density and molecular weight indicated above from the ideal equation of state

$$T = \frac{PM}{\rho R^*}$$

e. Speed of Sound - c

For altitudes greater than 301,000 feet the equation for the speed of sound is the same one as used for the lower altitudes, but the ratio of the specific heats is no longer assumed to be equal to 1.40. The ratio of the specific heats varies with the molecular weight according to the expression

$$\gamma = \frac{c_p}{c_p - R^*/M}$$

The remaining properties are calculated using identical expressions to those outlined in the Section (13.1) for altitudes less than 301,000 feet.

III. NUMERICAL TECHNIQUES

14. Introduction

The analysis carried out in Chapter II lead, as far as the mathematical problem formulation is concerned, to three initial value problems and one matrix manipulation. The three initial-value problems are to establish

(i) the initial conditions for the coolant fluid, defined by Eqs. 3.42 through 3.45,

(ii) the dynamics of the coolant flow, defined by Eqs. 3.40 through 42 and 44,

(iii) the temperature field throughout the system, defined by Eqs. 2.18 through 2.22 for the fin, Eqs. 3.39 and 46 for the coolant, Eqs. 4.6, 7 and 8 for the channel wall, Eqs. 4.7, 5.3 and 5 for the protection layer, or Eq. 4.11 replacing Eqs. 2.19, 4.6, 7 and 8 and 5.3 and 5 in the case where Eq. 4.9 is satisfied. These equations must be supplemented by the specification of the initial, non-dimensional temperature everywhere in the system.

Each initial-value problem is solved by a fourth-order Runge-Kutta-Simpson integration discussed in Section 15.

The radiosity equation, Eq. 6.17 requires the matrix manipulation, namely either the solution of a system of linear algebraic equations, or a matrix inversion whenever the optical properties of the thermal control coating are considered temperature independent. Either task is accomplished by elementary row operations which transform, in a single process, the augmented coefficient matrix into a row-reduced echelon matrix. The reader is referred for this transformation to standard texts on linear algebra (Ref. 9)

Additional mathematical operations are programmed as subprograms which may be generally applied and which are discussed in Sections 16 through 21 in this order: an evaluation of polynomials in one variable, an Aitken interpolation, first and second differentiation, definite integration and integration with variable upper integration limit for functions of equally spaced arguments.

15. The Runge-Kutta-Simpson Integration

Two types of initial-value problems are to be solved in this program. The first type includes Item (i) and (ii) mentioned in the Introduction, namely the fluid dynamics exclusive of the transient fluid temperature field, and involves ordinary, first-order differential equations, linear in the derivatives with respect to the axial distance ζ , that is Eqs. 3.42, 43 and 44. The equations are solved explicity for these derivatives so as to take on the general form of Eq. 15.1:

$$\frac{dy_i}{dx} = f_i(x,y_1,y_2,\ldots,y_n) \tag{15.1}$$

$$y_i(0) = a_i \qquad , \quad i = 1,2,\ldots, N \tag{15.2}$$

Equation 15.2 constitutes the appropriate initial conditions. The other type of initial-values problem, mentioned as item (iii) in the Introduction, involves partial differential equations which are linear and of the first order in the time-derivatives; moreover, all equations, Eqs. 2.18, 3.46, 4.8 and 5.3, are explicit in the time derivatives. Having subdivided the radiator system into intervals, equally spaced in each appropriate domain (fluid, wall, fin, etc.), and then written the different equations corresponding to each one of the resulting N interior nodal points, one may discretize the spatial derivatives occuring on the right-hand sides of the partial differential equations. The result is a set of ordinary differential equations, with time as the independent variable but of a form which is identical to Eq. 15.1. Equation 15.2 is given by the initial temperature distribution; a uniform temperature was chosen for the first start of the integration ($a_i = a$; $i = 1, 2, \ldots, N$), subsequent integrations during optimization runs are expected to start from the previously computed steady-state temperature distributions. The boundary conditions may be satisfied in three different ways. Either, the temperatures are computed directly from the finite-difference equation representing the boundary conditions at the end of every time step, or secondly, the boundary conditions may be included into the system of Eqs. 15.1 after differentiation with respect to time, or lastly, an equation of the form of Eqs. 15.1 may be derived directly from a control volume bounded at one side by the boundary of interst. We have utilized all three possibilities.

Discretization introduces obviously a truncation error; all spatial derivatives are represented consistently with a truncation error proportional to the square of the local spatial interval (see Sect. 18) but higher-order terms may be included anytime by modifying a single program unit each for the first and second derivatives.

The system of Eqs. 15.1 and 15.2 is solved by a fourth-order Runge-Kutta integration, that is if the f_i in Eqs. 15.1 have continuous fourth-order derivatives, the time-related accuracy of the integration is of order four (Refs. 26 and 27). Under much weaker conditions, namely uniform Lipschitz continuity (Ref. 26 . the accuracy is still first-order and stability is secured. It may be noted that the Lipschitz continuity is also the prerequisite for uniqueness of the solution to Eqs. 15.1.

An existing single-precision, floating-point Runge-Kutta-Simpson SUBROUTINE RKS, written by R. Schubert at the Aerospace Corporation was used. Its fixed-step integration mode was employed for the integration of the fluid flow variables along the channel axis, while the transient temperature field was integrated with variable time steps, chosen automatically so as to keep the "truncation error" per time step below a specified limit. The absolute and relative errors A_i and R_i are specified, by the user, for each variable y_i , and after every Runge-Kutta integration step a Simpson integration is carried out over the same interval and with the intermediate derivatives as used in the former integration. From the difference D_i between the two integrations is calculated the "truncation error" measure

$$E_m = \max E_i = \left| \frac{D_i}{A_i + R_i \left|y_i\right|} \right| \quad , \qquad i = 1,\ldots, N \tag{15.3}$$

and if $0.75 < E_m$ then the time step DEL is divided by $\sqrt[5]{10}$ and the step is repeated, if $0.075 < E_m \leq 0.75$ then DEL is multiplied by $\sqrt[5]{10}$ for the subsequent step.

All variables y_i are set equal to their initial values in the program which calls RKS. During the integration RKS interacts directly with two other subroutines, namely DERIV and CNTRL, whose names are the first elements of the argument list in the call statement. The first subroutine, DERIV, serves to compute all N derivatives dy_i/dx in accordance with Eqs. 15.1. The second subroutine, CNTRL, controls the output during integration and the termination of integration. Output of current values of all varibales along with important system parameters is provided under two different integration modes: general transient system simulation, MSTØR = 0 in NAMELIST/RUNØPT/, produces output in arbitrarily chosen, fixed time steps, DTWRTE, up to the final time TEND, both specified in NAMELIST/RUNØPT/ and in hours; the second mode serves to compute the steady-state conditions and is invoked by setting MSTØR = 1 and by specifying the number LIMWRT of time intervals DTWRTE at which output is desired.

The integration under the second mode (MSTØR = 1) is terminated as soon as the expected truncation error due to program termination is less than five times the specified relative error per time step, RLIMIT, that is R_i in Eq. 15.3. The largest truncation error associated with the j-th time step is anticipated on the basis of Eqs. 1.1 and 2 as follows

$$\delta_j = \max_i \delta_{i,j} = \max_i \left\{ \Delta_j\tau \; \frac{\dot{y}_{i,j}}{\ell n \dfrac{\dot{y}_{i,j-1}}{\dot{y}_{i,j}}} \right\} \quad , \quad i = 1,2,\ldots, N \tag{15.4}$$

The maximum is taken from all N modal points, $\Delta_j\tau$ is the current integration step size with index j, and $\dot{y}_i$ stands for the dy_i/dx in Eqs. 15.1.

The argument list of RKS (and RKSF) is as follows:

(i) DERIV, name of derivative subroutine
(ii) CNTRL, name of control subroutine

} declared as EXTERNAL in calling program

(iii) Y , array name*, containing the y_i's in Eqs. 15.1 **

(iv) DY, array name*, containing the dy_i/dx in Eqs. 15.1

(v) A , array name*, containing the A_i's in Eq. 15.3**

(vi) R , array name*, containing the R_i's in Eq. 15.3**

(vii) T , the independent variable X in Eqs. 15.1**

---

* declared in calling program as array with dimension size equal to the number of differential equations.

** to be specified prior to the calling statement.

(viii) DEL, the integration step**, DEL $\neq$ 0

(ix) N , (integer) the number of equations**

(x) IFVD = 0: variable step size **, see Eq. 15.3

= 1: fixed step size equal to DEL

(xi) IBKP = 0: adjust step size at most once before repeat,**

= 1: adjust in accordance to Eq. 15.3

(xii) NTRY = 1: continue integration**, normal start

= 2: return from RKS

= 3: repeat last step with new DEL

= 4: restart

(= 2, = 3, = 4: to be changed in CNTRL)

(xiii) IERR = 0, normal integration

= -1 indicates singularity when IFVD = 0

= +1 indicates denominator vanishes in Eq. 15.3 at some time during integration.

(xiv) through (xx) are array names* with which the user need not to be concerned except YS that contains the y 's in Eq. 15.1 at the previous times step: DELY, PD, SD, YS, YST, DYST, YSIMP.

The SUBRØUTINE DERIV communicates with RKS only via its argument list which contains, in this order, Y, DY, and T, as specified above under iii, iv, and vii. Here, the current values of Y and T are supplied to DERIV, and the corresponding values of DY returned by DERIV to RKS.

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*declared in calling program as array with dimension size equal to the number of differential equations.

**to be specified prior to the calling statement.

The SUBRØUTINE CNTRL communicates with RKS also via its argument list. It contains Y, DY, DEL, T, NTRY, IFVD as specified above under iii, iv, viii, vii, xii and x, respectively. From the array Y are available for output all the results of integartion. The time step may be modified to reach a specific time value; and by specifying NTRY one controls the integration process from within CNTRL during the integration. Finally, one may switch from variable to fixed step size during the integration by resetting IFVD.

This completes the discussion of the integration of both ordinary and partial differential equations as they occur in the analysis developed in Chapter II. The discussion is deemed sufficient to enable the user to apply the RKS routine to other problems as well.

16. The Evaluation of Polynomials

All polynomials

$$z = a_o + a_1x + a_2x^2 + \dots + a_Nx^N \tag{16.1}$$

are carried out in a function subprogram based on the simple, efficient recurrence relation

$$\begin{aligned} z_o &= a_N \\ z_{i+1} &= x \cdot z_i + a_{N-i-1} \\ &\qquad i = 0,1,\dots, N-1 \\ z &= z_N \end{aligned} \tag{16.2}$$

The coeffieints a , i = 0, 1, ..., N must be placed, in the calling program, into an array of dimension (N + 1), N is an arbitrary positive integer.

The procedure is coded as a function subprogram called PØLY(X,A,M) , where X is the argument x in Eq. 16.1, A is the array containing M = N + 1 elements starting with A(1) = a .

17. Aitken Interpolation

Experimental data and supporting computer results which are not represented by analytic expressions are interpolated by Aitkens interpolation technique (Ref. 27). An (n + 1)-point Lagrangian interpolation is reduced to a sequence of 1/2 n (n + 1) linear interpolations. The interval spacing is arbitrary; and any number $M \geq n$ of ordered pairs (x_i, y_i) can be supplied in the calling program. The n points of interpolation are spaced equally about the point x of interpolation. It should be noted, however that unless n = N or n = 2 the result y(x) is not continuous in general. Care must also be taken that all nodes x_1, x_2, ... are distinct.

The procedure is coded as a function subprogram called YINT(X,Y,M,N,P), where X and Y are the names of arrays that have the same dimension M and contain the ordered pairs (x_i, y_i), i = 1,2, ..., M such that $x_1 < x_2 < \dots x_M$. The number n of points used for the interpolation is specifed as N, and the value of x at which to inerpolate is supplied as P. Note that $2 \leq N \leq M$ must be satisfied.

18. Numerical Differentiation

The first and second derivative of tabulated functions of equally spaced arguments is carried out in SUBRØUTINE DDY(Y,DY,DX,N) and in SUBRØUTINE D2DX2(Y,D2Y,DX,N), respectively. Each subroutine requires that two arrays be declared in a DIMENSIØN statement in the calling program, to have at least N elements; one array for the set of ordinates $Y \to y_i$ supplied by the calling program, the other array for the return of the results, that is $DY \to dy_i/dx$ or $D2Y \to d^2y_i/dx^2$. The argument interval Δx and the number of ordinances y_i are to be specified as DX and N, respectively. However, in order that terms of order Δx be retained including at the endpoints of the domain, N must be no less than 3 for DDX and 4 for D2DX2. The truncation error is of order $y'''(\Delta x)^2$ and $y^{IV}(\Delta x)^2$, respectively, for DDX and D2DX2.

19. Numerical Integration

The definite integral

$$F = \int_{X_1}^{X_N} y(x_i)\,dx \quad , \quad 1 \leq i \leq N; \qquad N \geq 2$$

and the indefinite integral

$$G_j = \int_{X_1}^{X_j} y(x_i)\ dx + G(x_1)$$

$$1 \leq i \leq N \quad ; \quad 1 < j \leq N \quad ; \quad N > 3$$

of a tabulated function y_i of an equally spaced argument, x_i, $x_1 + \Delta x$, $x_1 + 2\ \Delta x, \ldots, x_1 + (N - 1)\Delta x$ is carried out by a modified Simpson integration in the FUNCTIØN DEFINT(Y,DX,N) Subprogram and in the SUBRØUTINE FINT(Y,YO,DX,N,F), respectively.

For DEFINT the ordinates y_i are to be placed in the array Y whose dimension of no less than N elements must be declared in the calling program. The argument interval and the number of ordinates are specified as DX and N, respectively.

For FINT there are two array declarations necessary in the calling program, both for at least N elements; one for the integrand $Y \rightarrow y_i$ and the other for the integral $F \rightarrow G_i$. The integration constant $G(x_1)$, the argument interval and the number of ordinates are to be supplied as YO,DX and N, respectively.

The truncation error of composite Simpson integration is

$$\frac{x_1 - x_N}{180} (\Delta x)^4\ y^{(iv)}\ (\xi) \quad \text{with} \quad x_1 \leq (\xi) \leq x_N.$$

APPENDIX A

STRUCTURAL MATERIAL PROPERTIES

Appendix A contains thermodynamic and mechanical properties for the three structural materials: copper, aluminum and beryllium. Four properties are evaluated for each material: specific heat at constant pressure, thermal conductivity, modulus of elasticity while (1/k)(dk/dT) is computed by differentiating the thermal conductivity relationship with respect to temperature.

All property relationships are presented in analytical form obtained by fitting a power polynomial through the data points. The data points listed in the tables are taken from the reference entered before each table. Numerical techniques used for the curve fitting process are explained in Section IV.

The polynomial expression for each property has been compared with the referenced data and within the listed temperature range has been found to deviate by no more than the percentage error indicated.

I. COPPER

1. Specfic Heat

Reference: Touloukian, Y. S., "Thermophysical Properties of High Temperature Solid Materials," Thermophysical Properties Research Center, Purdue University, Vol. 1, 1967, pp. 456-7.

Data Points:

T	c_p
600 R	0.0920 Btu/(lbm R)
1000	0.0975
2000	0.1112

Polynomial Fit:

Temperature Range: 400 - 2000 R

Equation:

$$c_p = (0.08375 + 1.375 \times 10^{-5}\ T\ R^{-1}) \times 32.174\ \text{Btu/ (slug R)} \quad (A.1)$$

Maximum Error: There was no difference between the computed value and the input data within the accuracy of the computer.

2. Thermal Conductivity

Reference: Touloukian, Y. S., "Thermophysical Properties of High Temperature Solid Materials," Thermophysical Properties Research Center, Purdue University, Vol. 1, 1967, pp. 458-9.

Data Points:

T	k
600 R	228.369 Btu/(hr ft R)
800	225.708
1000	222.805
1200	219.418
1400	215.306

Polynomial Fit:

Temperature Range: 500 - 1800 R

Equation:

$$k = (228.369 - 2.62067\theta - 0.04033\theta^3)\ \text{Btu/(hr ft R)} \qquad \text{(A.2)}$$

where

$$\theta = \frac{T - 600.0R}{200.0R} \qquad \text{(A.3)}$$

Maximum Error: 0.87%

3. <u>Temperature Variation of Thermal Conductivity</u>

Eq. A. 2 was differentiated with respect to temperature to yield

$$\frac{1}{k}\ \frac{dk}{dT} = \frac{1}{200}\ \frac{(-2.62067 - 0.121\ \theta^2)}{(228.369 - 2.62067\theta - 0.04033\ \theta^3)}\ R^{-1} \qquad \text{(A.4)}$$

4. Modulus Elasticity:

Reference: "Material Manual," TRW Equipment Laboratories, February 1966, Report No. ER-6756, Contract No. NAS 9-4884, Fig. 50.

Data Points:

T	Y
0 F	16.55×10^6 lbf/in^2
400	14.35
800	9.65
1200	3.82

Polynomial Fit:

Temperature Range: 500 - 1600 R

Equation:

$$Y = (16.55 - 0.4933\theta - 1.935\theta^2 + 0.2283\theta^3) \times 1.44 \times 10^8 \ (\text{lb f/ft}^2) \tag{A.5}$$

where

$$\theta = \frac{T - 459.67 \ \text{R}}{200 \ \text{R}} \tag{A.6}$$

Maximum Error: 0.44%

II. ALUMINUM 7075

1. Specific Heat

Reference: Touloukian, Y. S., "Thermophysical Properties of High Temperature Solid Materials," Thermophysical Properties Research Center, Purdue University, Vol. 2-11. 1967, pp. 810-11.

Data Points:

T	c_p
400 R	0.182 Btu/(lbm R)
600	0.209
800	0.226
1000	0.244
1200	0.270

Polynomial Fit:

Temperature Range: 300 - 1200 R

Equation:

$$c_p = (0.182 + 0.03616\theta - 0.011417\theta^2 + 0.00233\theta^3 - 0.000083\theta^4) \times 32.174 \text{ Btu/(slug R)} \quad (A.7)$$

where

$$\theta = \frac{T - 400 \text{ R}}{200 \text{ R}} \quad (A.8)$$

Maximum Error: 0.34%

2. Thermal Conductivity

Reference: Touloukian, Y. S., "Thermophysical Properties of High Temperature Solid Materials," Thermophysical Properties Research Center, Purdue University, Vol. 2-11, pp. 812-13.

Data Points:

T	k
400 R	88.50 Btu/(hr ft R)
600	100.395
800	105.96
1000	104.024
1200	99.18

Polynomial Fit

Temperature Range: 300 - 1200 R

Equation:

$$k = (88.5 + 13.0665\theta + 0.33275\theta^2 - 1.758\theta^3 + 0.25375\theta^4) \quad \text{Btu/(hr ft R)} \tag{A.9}$$

where

$$\theta = \frac{T - 400\ R}{200\ R} \tag{A.10}$$

Maximum Error: 0.96%

3. Temperature Variation of Thermal Conductivity:

Equation A.9 was differentiated with respect to temperature to yield

$$\frac{1}{k}\frac{dk}{dT} = \frac{1}{200}\frac{(13.0665 + 0.6655\theta - 5.25\theta^2 + 1.015\theta^3)}{(88.5 + 13.0665\theta + 0.33275\theta^2 - 1.758\theta^3 + 0.25375\theta^4)} \tag{A.11}$$

4. Modulus of Elasticity

Reference: "Material Manual," TRW Equipment Laboratories, February 1966, Report ER-6756, NAS 9-4884, Fig. 50.

Data Points:

T	Y
0 F	10.71×10^6 lbf/in^2
200	9.90
400	8.50
600	6.15

Polynomial Fit:

Temperature Range: 500 - 1200 R

Equation:

$$Y = (10.71 - 0.63\theta - 0.115\theta^2 - 0.06\theta^3) \times 1.44 \times 10^8 \text{ lbf/ft}^2 \tag{A.12}$$

where

$$\theta = \frac{T - 459.67\ R}{200\ R} \qquad (A.13)$$

Maximum Error: 0.38%

III. BERYLLIUM (1/2 - 3% Be O)

1. Specific Heat

Reference: Touloukian, Y. S., "Thermophysical Properties of High Temperature Solid Materials," Thermophysical Properties Research Center, Purdue University, Vol. 6-II, 1967, pp. 753-4.

Data Points:

T	c_p
800 R	0.536 Btu/(lbm R)
1000	0.585
1200	0.622
1400	0.652
1600	0.680

Polynomial Fit:

Temperature Range: 400 - 1700 R

Equation:

$$c_p = (0.536 + 0.05667\theta - 0.00850\theta^2 + 0.000830\theta^3) \times 32.174 \text{ Btu/(slug R)} \tag{A.14}$$

where

$$\theta = \frac{T - 800 \text{ R}}{200 \text{ R}} \tag{A.15}$$

Maximum Error: 0.88%

2. Thermal Conductivity

Reference: Touloukian, Y. S., "Thermophysical Properties of High Temperature Solid Materials," Thermophysical Properties Research Center, Purdue University, Vol. 6-II, 1967, pp. 757-9.

Data Points:

T	k
400 R	108.863 Btu/(hr ft R)
600	98.944
800	89.751
1000	80.80
1200	72.091

Polynomial Fit :

Temperature Range: 400 - 1700 R

Equation:

$$k = (108.863 - 10.5643\theta + 0.82683\theta^2 - 0.20167\theta^3 + 0.020167\theta^4)\ \mathrm{Btu/(hr\ ft\ R)} \quad (A.16)$$

where

$$\theta = \frac{T - 400\ R}{200\ R} \quad (A.17)$$

Maximum Error: 0.90%

3. Temperature Variation of Thermal Conductivity

Equation A.15 was differentiated with respect to temperature to yield

$$\frac{1}{k}\frac{dk}{dT} = \frac{1}{200}\,\frac{(-10.5643 + 1.65367\theta - 0.60501\theta^2 + 0.080668\theta^3)}{(108.863 - 10.5643\theta + 0.82683\theta^2 - 0.20167\theta^3 + 0.020167\theta^4)}\ R^{-1} \qquad (A.18)$$

4. Modulus of Elasticity

Reference: "Material Manual," TRW Equipment Laboratories, February 1966, Report ER-6756, Contract No. NAS 9-4884, Fig. 51.

Data Points:

T	Y
0 F	44.36×10^6 lbf/in^2
400	40.41
800	33.95
1200	21.80

Polynomial Fit:

Temperature Range: 500 - 1700 R

Equation:

$$Y = (44.36 - 3.755\theta + 0.335\theta^2 - 0.53\theta^3) \times 1.44 \times 10^8 \text{ lb f/ft}^2 \qquad (A.19)$$

where

$$\theta = \frac{T - 459.67\ R}{400\ R} \tag{A.20}$$

Maximum Error: 0.28%

APPENDIX B

COOLANT FLUID PROPERTIES

I. HELIUM

1. Equation of State Explicit in Pressure

Reference: Akin, S. W., Trans. ASME, Vol. 72, p. 751, 1950.

Equation: The National Bureau of Standards has published a Bendict-Webb-Rubin equation for helium; this equation was found to be valid only up to the specified pressure limit of 3000 lbf/in^2. Preference was therefore given to the following Beattie-Bridgeman equation:

$$p = \rho^2 \, [RT(1 - a)(\frac{1}{\rho} + B_1) - A] \tag{B.1}$$

where

$$a = \frac{c}{T^3} \rho$$

$$A = A_1 \, (1 - a \, \rho)$$

The values of the constants in Eq. B.1, in MKSA units, are:

$R = 2.07702 \times 10^3$

$A = 1.369595 \times 10^2$

$B = 3.5002295 \times 10^{-3}$

$C = 1.0000658 \times 10^1$

$a = 1.496103 \times 10^{-2}$

Temperature Range: 160 - 860 R

Pressure Range: 2116 - 360000 lbf/ft^2

Maximum Error: 0.095%

2. Equation of State Explicit in Density

Since the equation of state is needed explicit in density, Eq. B.1 was solved using Newton-Raphson iteration method along an isotherm to give

$$\rho_{i+1} = \rho_i - \frac{p - p(\rho_i)}{(\partial p/\partial \rho)_T} \tag{B.2}$$

Using Eq. B.1, one obtains

$$\left(\frac{\partial p}{\partial \rho}\right)_T = RT + 2(RB_1T - A_1 - \frac{CR}{T^2})\rho + 3(A_1 a - \frac{CRB_1}{T^2})\,\rho^2 \tag{B.3}$$

3. Isobaric Thermal Expansion Coefficient

The isobaric thermal expansion coefficient is defined by the equation

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \tag{B.4}$$

Since the equation of state (Eq. B.1) is explicit in the pressure, one can write β as:

$$\beta = \frac{1}{\rho}\,\frac{(\partial p/\partial T)_\rho}{(\partial p/\partial \rho)_T} \tag{B.5}$$

or

$$\beta = \frac{R[\rho + (B_1 + \frac{2C}{T^3})\rho^2 + \frac{2CB_1}{T^3}\rho^3]}{\rho[RT + 2\rho(RB_1T - A_1 - \frac{CR}{T^2}) + 3\rho^2(A_1 a - \frac{CRB_1}{T^2}\,]} \tag{B.6}$$

4. Isothermal Compressibility

The isothermal compressibility is defined by the equation

$$\kappa = \frac{1}{\rho} \left(\frac{\partial\rho}{\partial p} \right)_T \tag{B.7}$$

Making use of Eq. B.3, the isothermal compressibility can be written as

$$\kappa = 1/\rho[RT + 2\rho(RB_1T - A_1 - \frac{CR}{T^2}) + 3\rho^2(A_1a - \frac{CRB_1}{T^2})] \tag{B.8}$$

5. Specific Heat at Constant Pressure:

Equation: Experimental and quantum statistical data for helium show that at zero-pressure, the specific heat at constant volume is independent of temperature

$$c_v^o = \frac{3}{2} R \tag{B.9}$$

Using Maxwell's equations, the following expression is obtained

$$c_v = c_v^o - T\int_{\rho_o}^{\rho} \left(\frac{\partial^2 p}{\partial T^2}\right)_\rho \frac{d\rho'}{(\rho')^2} \tag{B.10}$$

From the equation of state, (Eq. B.1) the integration is carried out in closed form to give

$$c_v = R[\frac{3}{2} + 6a\ (1 + \frac{\rho}{2} B_1)] \tag{B.11}$$

The relation between specific heat at constant pressure and that at constant volume is given by:

$$c_p = c_v + \frac{T\beta^2}{\rho\kappa} \tag{B.12}$$

Temperature Range: 180 - 900 R

Pressure Range: 2116 - 216000 lbf/ft

Maximum Error: 0.58%

6. Enthalpy

The variation of internal energy with both temperature and density is

$$du = c_v dT + [p - T\ (\frac{\partial p}{\partial T})_\rho\ ]\ \frac{d\rho}{\rho^2}$$

carrying out the integration along an isochore and an isotherm, one obtains

$$u = u_o + R\ [\frac{3}{2}\ (T - T_o) + 3\ \rho c\ (1 + \frac{B_1}{2})\ (\frac{1}{T_o^{\ 2}} - \frac{1}{T^2})] + (\frac{3\ R\ C}{T^2} + A_1)$$

$$(\rho_o - \rho) + \frac{1}{2}\ (\frac{3\ C\ R\ B_1}{T^2} - A_1\ a)\ (\rho_o^{\ 2} - \rho^2)$$

where $u_o = 3.9922 \times 10^4$ j/kg

$T_o = 10.938889$ K

$\rho_o = 4.669193$ kg/m^3

The enthalpy may then be determined from the equation

$$h = u + \frac{p}{\rho}$$

7. Thermal Conductivity

Reference: Akin, S. W., Trans. ASME, Vol. 72, p. 751, 1950

Data Points:

T	k
160 R	0.0404 Btu/(hr ft R)
360	0.0676
560	0.090
760	0.1094

Polynomial Fit:

Temperature Range: 160 - 860 R

Equation:

$$k = (0.0404 + 0.0302\,\theta - 0.0033\,\theta^2 + 0.0003\,\theta^3)\ \text{Btu/(hr ft R)} \quad \text{(B.13)}$$

where

$$\theta = \frac{T - 160\ R}{200\ R}$$

Maximum Error: 0.54%

8. Temperature Variation of Thermal Conductivity

Eq. B. 13 was differentiated with respect to temperature to yield

$$\frac{1}{k}\frac{dk}{dT} = \frac{1}{200} \; \frac{(0.0302-0.0066\ \theta+0.0009\ \theta^2)}{(0.0404+0.0302\ \theta-0.0033\ \theta^2+0.0003\ \theta^3} \; \frac{1}{R} \qquad (B.14)$$

9. Dynamic Viscosity

Reference: Akin, S. W., Trans. ASME, Vol. 72, p. 751, 1950

Equation: Viscosity correlations are ususally based on the concept of residual viscosity:

$$\psi_1\ (\rho) = \mu(\rho,T) - \mu^*(T) \qquad (B.15)$$

where

ψ_1 is the residual viscosity (function of density alone).

μ^* is the dynamic viscosity at atmospheric pressure.

For helium, the dynamic viscosity is given by:

$$\mu = \mu^* = 2.58394 \times 10^{-5} T/°R)^{0.647} \ \text{slug/(ft hr)} \qquad (B.16)$$

Temperature Range: 160 - 660 R

Maximum Error: 0.29%

II SILICON OIL

The following properties are for Dow Corning 200 Silicon Oil (1 Centistoke at 77 F).

1. Isothermal Compressibility

Reference: Gunst, S. B., "Density-Pressure Relationships for Two Low-Viscosity Dimethyl Siloxanes," Trans. ASME 72, May 1950, pp. 401-7.

Data Points: Variation of κ with temperature at 0 psig and 500 psig are given below:

t	κ_o	κ_{500}
100 F	12.35×10^{-6} in^2/lbf	11.60×10^{-6} in^2/lbf
150	16.05	14.94
200	20.45	18.82
250	26.25	23.86
300	36.55	31.88

Polynomial Fit:

Temperature Range: 560 - 760 R

Pressure Range: 2116 - 74116 lbf/ft^2

Equation: The variation of κ_o with temperature at 0 psig is given by

$$\kappa_o = (12.35 + 2.9833\,\theta + 1.1\,\theta^2 - 0.48333\theta^3 + 0.1\,\theta^4) \times 10^{-6} \text{ in}^2/\text{lbf} \quad \text{(B.17)}$$

where $\theta = \dfrac{T - 559.67 \text{ R}}{50 \text{ R}}$

κ is assumed to vary linearly on the above range of pressure, hence

$$\kappa = a + b\,p \quad \text{(B.18)}$$

where

$$a = \kappa_o$$

$$b = \left(\frac{\partial \kappa}{\partial p}\right)_T \simeq \frac{\kappa_{500} - \kappa_o}{500 \text{ psi}}$$

and p is the pressure in psig

Fitting a power polynomial through $\left(\frac{\partial \kappa}{\partial p}\right)_T$ with the same values for temperature as indicated in the table results in the equation

$$b = (-1.5 - 0.0133\,\theta - 1.18\,\theta^2 + 0.57333\,\theta^3 - 0.1\,\theta^4) \times 10^{-9} \text{ in}^4/\text{lbf}^2 \quad \text{(B.19)}$$

Maximum Error: There was no difference between the computed and the input data within the accuracy of the computation.

2. Equation of State Explicit in Density

Reference: Gunst, S. B., "Density-Pressure Relationships for Two Low-Viscosity Dimethyl Siloxanes," Trans. ASME, May 1950, pp. 401-7.

Data Points: Values for the variation of density with temperature at 0 psig are given below:

t	ρ_o
150 F	0.7767 gm/cm^3
200	0.7479
250	0.7188
300	0.6900

Polynomial Fit:

Temperature Range: 540 - 760 R

Pressure Range: 2116 - 146116 lbf/ft^2

Equation:

$$\rho_o = (0.7767 - 0.0288\ \theta) \times 1.94 \quad slug/ft^3 \tag{B.20}$$

where

$$\theta = \frac{T - 609.67\ R}{50\ R}$$

The variation of density with pressure is given by

$$dz = \frac{d\rho}{\rho} = -\ \beta\ dT + \ \kappa\ dp \tag{B.21}$$

Integration along the isotherm T_o = 609.67 R and from p' = 0 psig to $p' = p$, using Eq. B.18 results in

$$z(p,T_o) = a(T_o)\ p + b\ (T_o)\ \frac{p^2}{2}$$

Integration along the isobar p, from $T' = T_o$, to $T' = T$, making use of Eq. B.25, yields

$$z(p,T)-z(p,T_o) = p\int_{T_o}^{T} a'(T')dT' + \frac{p^2}{2}\int_{T_o}^{T} b'(T')dT' - \int_{T_o}^{T} c(T')dT'$$

which after simplification reduces to

$$\rho = \rho_o \, e^{ap + \frac{1}{2} b \, p^2} \tag{B.22}$$

Maximum Error: 0.128%

3. Equation of State Explicit in Pressure

Since the equation of state is needed explicit in pressure, Eq. B.22 was rearranged to yield

$$p = \frac{1}{b} \left[-a + \sqrt{a^2 + 2b \ln \frac{\rho}{\rho_o}} \right] \tag{B.23}$$

4. Isobaric Thermal Expansion Coefficient

From Eq. B.20, the zero-pressure isobaric thermal expansion coefficient can be written as:

$$\beta_o = - \frac{1}{\rho_o} \left(\frac{\partial \rho_o}{\partial T}\right)_p$$

or

$$\beta_o = \frac{0.0288}{50(0.7767 - 0.0288\ \theta)} \quad \frac{1}{R} \tag{B.24}$$

Making use of Eq. B.21, together with the principle of an exact differential, one may write

$$\left(\frac{\partial \beta}{\partial p}\right)_T = - \left(\frac{\partial \kappa}{\partial T}\right)_p$$

From Eq. B.18, the variation of β with both pressure and temperature is given by

$$\beta = \beta_o - a' p - \frac{b'^2}{2} p^2 \tag{B.25}$$

where the prime superscript indicates differentiation with respect to temperature. The expressions for a and b as a function of temperature are given in Eqs. B.17 and 19, respectively.

5. Specific Heat at Constant Pressure

Reference: Dow Corning, Bulletin 05-145, February 1966.

Data Points: The available data for the variation of zero pressure specific heat at constant pressure for 2 centistokes are:

t	c_p^o	
80 F	0.448	Btu/(lbm F)
160	0.454	
240	0.463	
320	0.476	
400	0.491	

Polynomial Fit:

Temperature Range: 540 - 860 R

Pressure Range : 2116 - 74116 lbf/ft^2

Equation: The above data for 2 centistokes silicon oil were multiplied by the ratio of c_p^o for 1 centistoke to 2 centistokes at 77°F, to give the following expression for the zero-pressure specific heat at constant pressure for 1 centistoke silicon oil

$$c_p^o = (0.46 + 0.00471\ \theta + 0.00141\ \theta^2 + 0.000043\ \theta^3) \times 32.174 \text{ Btu/(slug R)} \tag{B.26}$$

where

$$\theta = \frac{T - 539.67 \text{ R}}{80 \text{ R}}$$

The variation of c_p with pressure is given by

$$c_p = c_p^o - T \int_{p_o}^{p} \left(\frac{\partial^2}{\partial T^2}\right)_p \left(\frac{1}{\rho}\right) \ dp' \tag{B.27}$$

Since the exponent in Eq. B.22 is small, the equation for the density, when expanded in a power series, may be truncated after the second term in the expansion. Applying Eq. B.27 to the two-term expression for density as a function of pressure and temperature by integrating along an isotherm T from p' = 0 psig to p' = p, results in the expression for

$$c_p = c_p^\circ - \frac{T\ I}{\rho_o} \tag{B.28}$$

where

$$I = z_1 p + z_2 p^2 + z_3 p^3 + z_4 p^4 + z_5 p^5$$

and

$$z_1 = 2\left(\frac{\rho_o'}{\rho_o}\right)^2$$

$$z_2 = \frac{1}{2}\left[\left(2\frac{\rho_o'}{\rho_o} a' - a''\right) - a z_1\right]$$

$$z_3 = \frac{1}{3}\left[a'^2 - \frac{b''}{2} + \frac{\rho_o'}{\rho_o} b'\right) - a\left(2\frac{\rho_o'}{\rho_o} a' - a''\right) + \frac{1}{2}(a^2 - b) z_1\right]$$

$$z_4 = \frac{1}{4}\,[a'b' - a\,(a'^2 - \frac{b''}{2} + \frac{\rho_o'}{\rho_o}\,a') + \frac{1}{2}\,(a^2 - b)\,(2\,\frac{\rho_o'}{\rho_o}\,a' - a'')$$

$$+ \frac{1}{2}\,abz_1]$$

$$z_5 = \frac{1}{10}\,[\frac{b'^2}{2} - 2a\,a'b' + (a^2 - b)\,(a'^2 - \frac{b''}{2} + \frac{\rho_o' b'}{\rho_o})$$

$$+ ab\,(2\,\frac{\rho_o'}{\rho_o}\,a' - a'') + \frac{1}{2}\,b^2\,z_1]$$

where the prime superscript indicates differentiation with temperature.

Maximum Error: For zero pressure specific heat at constant pressure the maximum error was 0.065%. For higher pressures no experimental data were available for comparison. However the expression for enthalpy was numerically differentiated with respect to temperature at constant pressure and compared with the computed values of specific heat at constant pressure. The comparison showed no difference within the accuracy of the computation.

6. Enthalpy

The variation of enthalpy with both pressure and temperature is given by:

$$dh = c_p^o\ dT + \frac{1}{\rho}\ [1 - T\beta]\ dp$$

This expression was integrated along the isobar p = 0 psig from T' = 539.65 R to T' = T, and then along an isotherm T from p' = 0 psig to p' = p, to give

$$h = \Big\{ 80(0.46 + 0.00471\,\theta + 0.00141\,\theta^2 + 0.000043\,\theta^3)$$

$$+ \frac{1}{\rho_o \cdot 337.37} \Big[-\frac{1}{20} b\, b'\, T\, p^5 - \frac{1}{8}(a\, b' + a'\, b)\, Tp^4$$

$$+ \frac{1}{6}\left(T(b' - a\, a') - b\left(1 + T\frac{\rho_o'}{\rho_o}\right)\right)p^3 + \frac{1}{2}\Big(a'\, T - a\Big(1$$

$$+ T\frac{\rho_o'}{\rho_o}\Big)\Big)\, p^2 + \left(1 + T\frac{\rho_o'}{\rho_o}\right) p \Big] \times 32.174 \Big\} \quad \text{Btu/slug} \qquad (B.29)$$

7. <u>Dynamic Viscosity</u>

Reference: Dow Corning, Bulletin 05-153, July 1966.

Data Points:

t	ν
0 F	1.98 centistokes
100	0.874
200	0.56
300	0.41

$$\ln \nu = (0.683 - 1.0845\ \theta + 0.3065\ \theta^2 - 0.04\ \theta^3) \qquad (B.30)$$

where ν is in centistokes

$$\mu = \nu\ \rho \qquad (B.31)$$

Maximum Error: 0.77%

8. Thermal Conductivity

Reference: Dow Corning, Bulletin 05-145, February 1966.

Data Points: The available data for the variation of thermal conductivity with temperature for 2 centistokes are:

t	k
-100 F	0.0674 Btu/(hr ft F)
100	0.0626
300	0.0578

Polynomial Fit:

Temperature Range: 360 - 860 R

Equation: The procedure that was used for specific heat at constant pressure was followed to get an expression for the variation of thermal conductivity with temperature for 1 centistoke silicon oil. The resulting expression for the thermal conductivity is given by

$$k = (7.0052 - 2.2105 \times 10^{-3} T\ R) \times 10^{-2}\ \text{Btu/(hr ft R)} \qquad (B.32)$$

Maximum Error: There was no difference between the computed and the input data within the accuracy of the computation.

9. Temperature Variation of Thermal Conductivity

Eq. B.32 was differenitated with respect to temperature to yield

$$\frac{1}{k}\ \frac{dk}{dT} = \frac{-\ 2.2105\text{x}10^{-3}}{7.0052\ -\ 2.2105\text{x}10^{-3}T/°R)} \qquad 1/R \qquad \text{(B.33)}$$

III NAK - 78.6

The following are the physical properties of NaK(78.6 wt% K) extracted from the latest version of the "Liquid Metals Handbook, Sodium and NaK Supplement" (to be published). Some typical properties are:

Melting Point: 92 F

Boiling Point: 1445 F

Surface Tension: 0.00739 lbf/ft at Melting point

1. Equation of State Explicit in Density

Data Points: Values for the variation of density with temperature at zero pressure is given by

t	ρ_o
200 F	53.21 lbm/ft^3
500	50.68
800	48.15
1100	45.62
1400	43.09

Polynomial Fit:

Temperature Range: 200 - 1400 °F

Equation:

$$\rho_o = (58.773064 - 0.008433\ T/R)/32.174\ \text{slug/ft}^3 \qquad (B.34)$$

Since the isothermal compressibility is assumed to be independent of pressure, Eq. B.22 for silicon reduces to

$$\rho = \rho_o \; e^{\kappa p} \tag{B.35}$$

where p is the gage pressure. Since the exponent is small, the expression for the density, when expanded in a power series, may be truncated after the second term and the variation of density with both pressure and temperature is given by

$$\rho = \rho_o \; (1 + \kappa \, p) \tag{B.36}$$

Maximum Error: At zero pressure, there was no difference between the computed and the input data, within the accuracy of the computation. For higher pressures there were no experimental data available for comparison.

2. Equation of State Explicit in Pressure

Since the equation of state is needed explicit in pressure, Eq. B.36 was rearranged to yield

$$p = \frac{1}{\kappa} \left(\frac{\rho}{\rho_o} - 1\right) \tag{B.37}$$

3. Isobaric Thermal Expansion Coefficient

The isobaric thermal expansion coefficient is defined to be

From Eq. B.34, the zero pressure isobaric thermal expansion coefficient is given by:

$$\beta_o = \frac{0.008433}{(58.773064 - 0.008433T)} \quad \frac{1}{R} \tag{B.38}$$

Due to the lack of experimental data, the isobaric thermal expansion coefficient was assumed to be independent of pressure.

4. Isothermal Compressibility

In view of the experimental difficulties associated with the measurement of isothermal compressibility at elevated temperatures, such data are not generally available for liquid metals. However, the well-known relationship between velocity of sound c, density ρ , and isentropic compressibility κ_s is

$$\kappa_s = \frac{1}{\rho c^2} \tag{B.39}$$

which makes an alternative approach to the problem possible, if velocities of sound can be measured. Under these circumstances the isothermal compressibility may be obtained from the relation

$$\kappa = \gamma \kappa_s \tag{B.40}$$

where

$$\gamma = \frac{c_p}{c_v}$$

The relation between c_p and c_v is given by

$$c_p - c_v = \frac{T\beta^2}{\rho\kappa} \tag{B.41}$$

From Eqs. B.40 and B.41, one gets

$$\kappa = \kappa_s + \frac{T\beta^2}{\rho c_p}$$

or

$$\kappa_o = \left\{ \frac{1}{\rho} \left(\frac{1}{c^2} + \frac{T\beta^2}{c_p} \right) \right\}_{\substack{T_o \\ p_o}} \tag{B.42}$$

Due to the lack of experimental data Eq. B.42 was evaluated at the absolute pressure p_o of one atmosphere and the temperature of T_o = 1260 R.

at T_o = 1260 R

ρ_o = 48.15 lbm/ft^3

c_o = 7544 ft/sec

β_o = 1.75149 x 10^{-4} 1/R

$C_{p,o}$ = 0.2091 Btu/(lbm R)

5. Specific Heat at Constant Pressure

Data Points: For zero-pressure specific heat at constant pressure are given by:

t	c_p^o
200 F	0.2255 Btu/(lbm F)
500	0.1239
800	0.2093
1100	0.2091
1400	0.2120

Polynomial Fit:

Temperature Range: 200 - 1400 F

Equation:

$$c_p^\circ = (0.2255 - 0.016292\ \theta + 0.00539\ \theta^2 - 0.000758\ \theta^3 + 0.000054\ \theta^4) \times 32.174\ \text{Btu/(slug R)} \tag{B.44}$$

where

$$\theta = \frac{T - 659.67\ R}{300\ R}$$

The variation of c_p with pressure is given by

$$c_p = c_p^o - T \int_{p_o}^{p} \frac{\partial^2}{\partial T^2} \left(\frac{1}{\rho}\right)_p dp'$$

Integrating along the isotherm T from p = 0 psig to p' = p, using Eqs. B.36 and B.38 results in

$$c_p = c_p^o - \frac{2 T \beta_o^2}{\rho_o \kappa} \ln (1 + \kappa p) \qquad \text{(B.45)}$$

Maximum Error: At zero pressure, the maximum error was 0.075%.

6. Enthalpy

The variation of enthalpy with both pressure and temperature is given by

$$dh = c_p \, dT + \frac{1}{\rho} [1 - T \beta] \, dp$$

The enthalpy was arbitrarily chosen to be zero near the melting point, or T = 469.67°R. The above expression was integrated along an isobar p = 0 psig from T' = 469.67°R to T' = T, and then along an isotherm T from p' = 0 psig to p' = p, to give

$$h = [300 \, (0.2255 \, \theta - 0.016292 \frac{\theta^2}{2} + 0.00539 \frac{\theta^3}{3}$$

$$- 0.000758 \frac{\theta^4}{4} + 0.000054 \frac{\theta^5}{5}) + \frac{1 - T\beta}{\rho_o \kappa} \ln (1 + \kappa \rho) \qquad \text{(B.46)}$$

$$\times \frac{1}{778.26}] \; 32.174 \quad \text{Btu/slug}$$

where ρ is in lbm/ft^3, κ is in ft^2/lbf and p is gage pressure in lbf/ft^2.

7. Thermal Conductivity

Data Points:

t	k
200 F	13.36 Btu/(hr ft F)
500	14.57
800	15.18
1100	15.03
1400	14.13

Polynomial Fit:

Temperature Range: 200 - 1400 F

Equation:

$$k = (13.36 + 1.414167\,\theta - 0.142083\,\theta^2 - 0.069167\,\theta^3 + 0.007083\,\theta^4)\ \text{Btu/(hr ft R)} \tag{B.47}$$

where

$$\theta = \frac{T - 659.67\ R}{300\ R}$$

Maximum Error: 0.2%

8. Temperature Variation of Thermal Conductivity:

Eq. B.47 was differentiated with respect to temperature to yield

$$\frac{1}{k}\frac{dk}{dT} = \frac{1}{300}\,\frac{(1.414167 - 0.284166\theta - 0.207501\theta^2 + 0.028332\theta^3)}{(13.36 + 1.414167\theta - 0.142083\theta^2 - 0.069167\theta^3 + 0.007083\theta^4)}\,\frac{1}{R} \tag{B.48}$$

9. Dynamic Viscosity

Data Points:

t	μ	
200 F	1.1316	lbm/(ft hr)
500	0.746	
800	0.534	
1100	0.411	
1400	0.340	

Polynomial Fit:

Temperature Range: 200 - 1400 F

Equation:

$$\mu = (1.316 - 0.896667\,\theta + 0.419833\,\theta^2 - 0.102833\,\theta^3 + 0.009667\,\theta^4)\,/32.174 \quad \text{slug/(ft hr)} \tag{B.49}$$

where

$$\theta = \frac{T - 659.67R}{300R}$$

Maximum Error: 1.2%

APPENDIX C

Optical Properties

Three optical properties are required in the radiative analysis discussed in Chapter 6, namely the total hemispherical emittance

$$\varepsilon(T) = \frac{1}{E_b(T)} \int_0^\infty \varepsilon_\lambda (T)\, E_{b,\lambda} (T) d\lambda \tag{C.1}$$

and the two auxiliary functions (see Eqs. 6.10 and 6.11)

$$XX(T_1, T_2) = \frac{1}{E_b(T_2)} \int_0^\infty \varepsilon_\lambda(T_1)\, \varepsilon_\lambda(T_2)\, E_{b,\lambda} (T_2) d\lambda \tag{C.2}$$

$$XXX(T_1, T_2, T_3) = \frac{1}{E_b(T_3)} \int_0^\infty \varepsilon_\lambda(T_1)\, \varepsilon_\lambda(T_2) \varepsilon_\lambda(T_3) E_{b,\lambda}(T_3) d\lambda \tag{C.3}$$

In view of the temperature independence of the spectral emittance for dielectrics, the two functions XX and XXX are functions of a single temperature, the temperature of the surface element represented by the last subscript on the left-hand sides of Eqs. 6.10 and 6.11:

$$XX(T) = \frac{1}{E_b(T)} \int_0^\infty \varepsilon_\lambda^{\ 2}\, E_{b,\lambda} (T) d\lambda \tag{C.4}$$

$$XXX(T) = \frac{1}{E_b(T)} \int_0^\infty \varepsilon_\lambda^{\ 3}\, E_{b,\lambda}(T) d\lambda \tag{C.5}$$

These functions are evaluated for the zinc oxide/potassium silicate coating Z-93 on the basis of spectral reflectance data measured by IITRI and published in the NASA Contractor Report No. 1420, titled Emissivity Coatings for Low-Temperature Space Radiators, by G. R. Cunnington, J. R. Grammer, and F. J. Smith, Lockheed Aircraft Corp., Sunnyvale, Calif., Sept. 1969, pp. 66 through 81.

The evaluated functions defined through Eqs. C.1, 4 and 5 are collocated by power polynomials of this form

$$f(T) = \sum_{i=o}^{N} a_i T^i \tag{C.6}$$

For the total hemispherical emittance, a fourth degree power polynomial was found to be satisfactory with

$a_0 = 0.8990103$

$a_1 = -0.1400633 \times 10^{-3}$

$a_2 = 0.387900 \times 10^{-6}$

$a_3 = -0.3937509 \times 10^{-9}$

$a_4 = 0.1015627 \times 10^{-12}$

For the auxiliary functions XX and XXX the coefficients are

	XX	XXX
$a_0 =$	0.7804112	0.6538383
$a_1 =$	$-0.5527205 \times 10^{-4}$	0.1144374×10^{-3}
$a_2 =$	0.2530228×10^{-6}	$-0.2432286 \times 10^{-7}$
$a_3 =$	$-0.3229181 \times 10^{-9}$	$-0.1437500 \times 10^{-9}$
$a_4 =$	$0.8854202 \times 10^{-13}$	$0.4947915 \times 10^{-13}$

APPENDIX D

The Simplified Radiator System Analysis

The simplified analysis is intended to support and to give guidance in the detailed and rigorous computer simulation of the Space Radiator Heat Rejection System. While it is possible to derive valuable insight in the radiator performance with relatively little effort, some results must be considered with great caution as presently it seems impossible to assess the extent of their validity in view of the simplifying assumptions made in the analysis.

Considered is a plane, rectangular panel, interrupted by n parallel tubes of length L and diameter d, all equally spaced and the distance $(H/n + d)$ apart, where $(d \ll H/n)$. Assuming that the panel rejects heat from both sides into an environment at the "equaivalent sink temperature" T_s and that the tube temperature is uniform and equal to T_b, one obtains for the power rejection from the panel area $2A = 2HL$

$$\dot{Q} = 2A\varepsilon\eta\ (T_b^{\ 4} - T_s^{\ 4}) \qquad \text{(D.1)}$$

Here, the fin effectiveness η is a known function $\eta(N_c)$ of the conductance parameter

$$N_c = \varepsilon\sigma\ T_b^{\ 3}\ (H/2n)^2 /\ (kt/2) \qquad \text{(D.2)}$$

and the sink temperature T_s. In Eqs. 1 and 2, ε represents the surface emittance, while k and t, in Eq. 2, stand for the thermal conductivity and the panel thickness, respectively.

The power rejected according to Eq. 1 must be transferred from the working fluid to the radiator tube. If the fluid enters the radiator at the rate $\dot{M}$, with the inlet temperature T_o and if the fluid has constant thermophysical properties then

$$\dot{Q} = \dot{M} c_p (T_o - T_b)(1 - e^{-u}) \tag{D.3}$$

where c_p represents the specific heat at constant pressure and

$$U = \frac{\pi dhL}{(\dot{M}/n)c_p} = \frac{4L}{d} \frac{N_{Nu}}{N_{Pr}N_{Re}} \tag{D.4}$$

which is a constant depending on tube geometry, fluid properties and operating conditions but not on radiator temperature (because the fluid properties are considred to be invariant along the tube). The Nusselt number N_{Nu} may be related to the Prandtl number N_{Pr} and the Reynolds number N_{Re} through

$$N_{Nu} = 5 + 0.025 (N_{Re}N_{Pr})^{0.8} \text{ for } N_{Pr} < 0.1,\ N_{Re} > 2300 \tag{D.5}$$

$$N_{Nu} = 0.023 (N_{Re}^{0.8} \ N_{Pr}^{0.3}) \quad \text{for } N_{Pr} > 0.1,\ N_{Re} > 2300 \tag{D.6}$$

$$N_{Nu} = 3.65 + \frac{0.0668 (N_{Re} \ N_{Pr} \ d/L)}{1 + 0.045 (N_{Re} \ N_{Pr} \ d/L)^{2/3}} \qquad N_{Re} \leq 2300 \tag{D.7}$$

Equations 1 and 3 define the tube temperature or fin base temperature T_b. After introducing the characteristic length L_o

$$L_o = \sqrt{\frac{\dot{M}\ c_p}{\varepsilon\sigma\ T_o^3}}$$

one may first normalize all dimensions

$$L^* = \frac{L}{L_o}\ ,\ d^* = \frac{d}{L_o}\ ,\ \ H^* = \frac{H}{L_o}\ ,\ \ t^* = \frac{t}{L_o}\ \ \text{and}\ A^* = \frac{A}{L_o^2} \tag{D.9}$$

and then the temperatures with respect to the known inlet temperature T_o:

$$\Theta_b = \frac{T_b}{T_o}\ ,\qquad \Theta_s = \frac{T_s}{T_o} \tag{D.10}$$

Combining Eqs. 1 and 3 gives

$$2\ A^*\eta(\Theta_b^4 - \Theta_s^4) - (1-\Theta_b)\ (1-e^{-u}) = 0 \tag{D.11}$$

as the equation which defines θ_b. However, the effectiveness η depends implicitely on θ_b through its dependence on the conductance parameter

$$N_c = \Theta_b^3\ \ \phi\left(\frac{H^*}{n}\right)^2\ \frac{1}{2t^*} \tag{D.12}$$

where ϕ is the system parameter, defined by

$$\phi = \left[\frac{\varepsilon\sigma\ T_o^{\ 3}\ \dot{M}\ c_p}{k^2}\right]^{1/2} \tag{D.13}$$

The system parameter ϕ, the characteristic length L_o, the Prandtl number N together with the ratio of fin to fluid thermal conductivities, k/k_{fl} , determine the tube temperature θ_b for any given geometry (L*, H*, t*, d*; n) and any given environment (θ_s). The Renyonlds number is given by

$$N_{Re} = \frac{4\phi}{\pi \, n d^*} \quad \frac{k/k_{f1}}{N_{Pr}} \tag{D.14}$$

Once the tube temperature θ_b is found then N_c and η are given through Eq. 12 and $\eta(N_c)$. The radiant power rejection can be expressed as the fraction of the "entrance enthalpy"

$$\dot{Q}^* = \frac{\dot{Q}}{\dot{M}\, c_p\, T_o} = 2\eta\, A^* \,(\Theta_b^4 - \Theta_s^4) \tag{D.15}$$

and the normalized fin weight by

$$\phi_f = \frac{M_f}{\rho_f L_o^3} = \frac{t^* \, \dot{Q}^*}{2\eta\,(\Theta_b^4 - \Theta_s^4)} \tag{D.16}$$

which leads to the fin mass requirement per power rejection

$$\psi_f = \frac{\phi_f}{\dot{Q}^*} = \frac{t^*}{2\eta\,(\Theta_b^4 - \Theta_s^4)} \tag{D.17}$$

and, finally, to the total mass requirement

$$\psi_{tot} = \psi_f \left[1 + F \frac{(d^*)^2}{H^* \, t^*} \right] \tag{D.18}$$

where the mass augmentation factor F is defined by

$$F = \pi \left[\frac{\rho_t}{\rho_f} \frac{d_m}{d} \frac{s}{d} \left(1 + \frac{\rho_p}{\rho_f} \frac{A_p}{A_t}\right) + \frac{\rho_{f1}}{4\rho_f}\right. \tag{D.19}$$

with ρ_t tube material density

ρ_f fin material density

$d_m =$ $(d + d_o)/2$, mean tube diameter

d inner tube diameter

$s =$ $(d_o - d)/2$

ρ_p density of protection layer

A_p cross-sectional area of protection layer

$A_t =$ $s\ d_m$

ρ_{fl} fluid density.

In summary, it can be seen that the performance of the heat rejection system considered here is determined by

(i) operating conditions

characterized by $\phi = \sqrt{\dfrac{\varepsilon\sigma\ T_o^3\ \dot{M}\ c_p}{k^2}}$

and $L_o = \sqrt{\dot{M}\ c_p/(\varepsilon\sigma\ T_o^3)}$

(ii) geometery L*, H*, t* and d*; n

(iii) fluid property N_{pr}, k/k_{fl}

The determination of the complete mass requirement per unit of power rejection is possible by the additional specification of the

(iv) Mass augmentation factor F

which determines the mass of tube, meteoroid protection and fluid, all per unit of corresponding fin mass.

The key equation, Eq. 11 has been programmed for numerical solution, using the programming language WIPL. Important quantities such as Q*, ψ_f and ψ_{tot} can also be evaluated. The fin effectiveness $\eta(N_c)$ is taken from LOVE, Radiative Heat Transfer where the results of a numerical analysis by Reynolds* are presented in graphical and numerical form for the case of

$\theta_s = 0$. The small correction on η for $0 \leq \theta_s \leq 0.8$ can be found in Radiation Heat Transfer by Sparrow and Cess.

Results obtained from this analysis at conditions for which large-scale computer calculations had been obtained are shown, for comparison, in Part I, Chapter C.

The WIPL code is listed below.

WIPL CODE

SIMPLIFIED ANALYSIS

```
1.000 COMMENT FIN WEIGHT AND HEAT REJECTION←
1.001 DECLARE FC[11],FFC[11],ETA[11],DETA[11],FETA[11]←
1.002 DECLARE FDETA[11],F1[11],F2[11]←
1.003 SET NL   = 0←
1.004 SET NPHI = 0←
1.005 SET NN   = 0←
1.006 SET NT   = 0←
1.010 TYPE "SPECIFY FC FOR ETA TABULATION"←
1.015 DO PART 2 FOR I=1,11←
1.020 TYPE "SPECIFY CORRESP. ETA-VALUES"←
1.025 DO PART 3 FOR I=1,11←
1.030 DO PART 4←
1.035 TYPE "SELECT RUNNING MODE"←
1.036 TYPE "   M=0 FOR COMPUTING HEAT REJECTION"←
1.040 TYPE "   M=1 FOR LENGTH VARIATION"←
1.041 TYPE "   M=2 FOR SYST. PARAMETER VARIATION"←
1.042 TYPE "   M=3 FOR TUBE NUMBER VARIATION"←
1.043 TYPE "   M=4 FOR THICKNESS VARIATION"←
1.050 ACCEPT M←
1.055 IF M EQ 1 THEN GO TO 1.300←
1.060 TYPE "SPECIFY GEOMETRY, LENGTH,THICKNESS,DEPTH"←
1.065 ACCEPT L,T,H←
1.070 TYPE "SPECIFY NUMBER OF TUBES AND DIAMETER"←
1.075 ACCEPT N,D←
1.076 IF M EQ 2 THEN GO TO 1.400←
1.080 TYPE "SPECIFY SYSTEM PARAMETER"←
1.085 ACCEPT PHI←
1.090 TYPE "SPECIFY FLUID PRANDTL NO. AND"←
1.091 TYPE "          RATIO OF FIN TO FLUID THERM. COND."←
1.095 ACCEPT PR,THCR←
1.096 TYPE "SPECIFY WEIGHT AUGMENTATION FACTOR"←
1.097 ACCEPT WA←
1.100 RE = 4.0*PHI*THCR/(3.141593*N*D*PR)←
1.101 LIMIT = 0←
1.105 IF PR LT 0.1 THEN GO TO 1.120←
1.106 IF (RE-2300.0) 1.107,1.110,1.110←
1.107 Z1 = PR*RE*D/L←
1.108 U  = (3.65+(0.0668*Z1)/(1.0+0.045*Z1**0.667))*4.0/Z1←
```

```
1.109 GO TO 1.125←
1.110 U  = 4.0*L/D*0.023*RE**(-0.2)*PR**(-0.7)←
1.115 GO TO 1.125←
1.120 U  = 4.0*L/D*(5.0+0.025*(RE*PR)**0.8)/(RE*PR)←
1.125 A  = L*H←
1.126 IF U LT 127.0 THEN GO TO 1.130←
1.127 B = 1.0←
1.128 GO TO 1.135←
1.130 B = 1.0-EXP(-U)←
1.135 SET THETA = 1.0←
1.140 FNC = PHI*(H*THETA/N)**2*THETA/(2.0*T)←
1.145 DO PART 6←
1.150 Y = 2.0*A*FETA[11]*THETA**4-(1.0-THETA)*B←
1.155 DEDT = FDETA[11]*3.0*FNC/THETA←
1.160 DY = 2.0*A*THETA**3*(THETA*DEDT+4.0*FETA[11])+B←
1.165 DTHETA = Y/DY←
1.167 LIMIT = LIMIT+1←
1.168 IF LIMIT EQ 11 THEN STOP←
1.170 IF ABS(DTHETA) LT 1.0E-04 THEN GO TO 1.185←
1.175 THETA = THETA-DTHETA←
1.180 GO TO 1.140←
1.185 THETA0 = 1.0-THETA←
1.186 IF LIMIT EQ 1 THEN THETA0 = DTHETA←
1.190 Q  = B*THETA0←
1.195 MASS = T*Q/(2.0*FETA[11]*THETA**4)←
1.200 MOQ  = MASS/Q←
1.201 PSITOT = MOQ*(1.0+WA*D**2/(H*T))←
1.205 PRINT FORM 1.210, RE,U,THETA←
1.206 PRINT FORM 1.212, FNC,FETA[11],PSITOT←
1.207 PRINT FORM 1.211, Q,MASS,MOQ←
1.210 FORM RE=@@@@@@@@@@, U=@@@@@@@@@@, THETA=.......,←
1.211 FORM  Q=.......,       M=@@@@@@@@@@,   MOQ =@@@@@@@@@@←
1.212 FORM NC=.......,     ETA=.......,    PSITOT =@@@@@@@@@@←
1.230 IF M EQ 0 THEN GO TO 1.035←
1.231 IF M GT 1 THEN GO TO 1.233←
1.232 IF MC LT NL THEN GO TO 1.345 ELSE STOP←
1.233 IF M GT 2 THEN GO TO 1.245←
1.234 IF MC LT NPHI THEN GO TO 1.445 ELSE STOP←
1.235 TYPE "MORE PROGRAMMING REQUIRED, SEE W. WULFF"←
1.299 STOP←
```

```
1.300 TYPE "SPECIFY THICKNESS, DEPTH, INITIAL • FINAL"←
1.305 TYPE "   LENGTHS AND NO. OF STEPS"←
1.310 ACCEPT T,H,L0,LEND,NL←
1.315 L = L0←
1.320 PRINT FORM 1.325, L←
1.325 FORM FOR L = @@@@@@@@@@←
1.330 DL = (LEND-L0)/(NL-1)←
1.335 MC = M←
1.340 GO TO 1.070←
1.345 MC = MC+1←
1.350 L = L+DL←
1.355 TYPE "      "←
1.360 GO TO 1.101←
1.400 TYPE "SPECIFY RANGE OF SYST. PARAMETER AND THE"←
1.405 TYPE "         NUMBER OF STEPS"←
1.410 ACCEPT PHIMAX,PHIMIN,NPHI←
1.415 PHI = PHIMIN←
1.430 DPHI = (PHIMAX-PHIMIN)/(NPHI-1)←
1.435 MC = M-1←
1.440 GO TO 1.090←
1.445 MC = MC+1←
1.450 PHI = PHI+DPHI←
1.455 TYPE "      "←
1.460 GO TO 1.100←
2.000 READ FC[I]←
3.000 READ ETA[I]←
4.000 H1 = FC[2]-FC[1]←
4.005 H2 = FC[3]-FC[1]←
4.010 X1 = (H2/H1)*ETA[2]←
4.015 X2 = -(H2/H1-H1/H2)*ETA[1]←
4.020 X3 = -H1/H2*ETA[3]←
4.025 DETA[1] = (X1+X2+X3)/(H2-H1)←
4.026 TYPE "  NC              ETA        DETA/DNC"←
4.027 FORM @@@@@@@@@@@@, •.•••••, @@@@@@@@@@@@@←
4.028 PRINT FORM 4.027,FC[1],ETA[1],DETA[1]←
4.030 DO PART 5 FOR I=2,10←
4.035 H1 = FC[10]-FC[9]←
4.040 H2 = FC[11]-FC[9]←
4.045 X1 = (2.0-H1/H2)*ETA[11]←
4.050 X2 = -H2/H1*ETA[10]←
```

```
4.055 X3 = -(2.0-H1/H2-H2/H1)*ETA[9]←
4.060 DETA[11] = (X1+X2+X3)/(H2-H1)←
4.065 IF ETA[11] LT 1.0E-06 THEN DETA[11] = 0.0←
4.070 PRINT FORM 4.027,FC[11],ETA[11],DETA[11]←
4.075 X1X2 = FC[3]-FC[2]←
4.080 AAA = -(FC[2]*ETA[3]-FC[3]*ETA[2]+X1X2)←
4.085 AAA = AAA/(FC[2]*FC[3]*X1X2)←
4.090 BBB = (1.0-ETA[2]-AAA*FC[2]**2)/FC[2]←
4.095 TYPE "FOR FNC NEAR ZERO, 1-ETA = AAA*FNC**2+BBB*FNC"←
4.100 PRINT FORM 4.105, AAA, BBB←
4.105 FORM AAA = @@@@@@@@@@@@, BBB = @@@@@@@@@@@@←
5.000 H2 = FC[I+1]-FC[I-1]←
5.005 H1 = FC[I]-FC[I-1]←
5.010 X1 = (H1/H2)*ETA[I+1]←
5.015 X2 = -(2.0-H2/H1)*ETA[I]←
5.020 X3 = (2.0-H1/H2-H2/H1)*ETA[I-1]←
5.025 DETA[I] = (X1+X2+X3)/(H2-H1)←
5.026 PRINT FORM 4.027,FC[I],ETA[I],DETA[I]←
6.000 IF FNC LT FC[3] THEN GO TO 6.020←
6.005 DO PART 7 FOR I=1,11←
6.010 DO PART 8 FOR I=1,11←
6.015 DO PART 9 FOR I=2,11←
6.016 GO TO 6.030←
6.020 FETA[11] = -((AAA*FNC+BBB)*FNC-1.0)←
6.025 FDETA[11] = -(2.0*AAA*FNC+BBB)←
6.030 REM REURN←
7.000 FETA[I] = ETA[I]←
7.005 FDETA[I] = DETA[I]←
8.000 FFC[I] = FC[I]-FNC←
9.000 DO PART 10 FOR J=I,11←
9.005 DO PART 11 FOR J=I,11←
10.000 XFC = FC[J]-FC[I-1]←
10.005 F1[J] = (FETA[I-1]*FFC[J]-FETA[J]*FFC[I-1])/XFC←
10.010 F2[J] = (FDETA[I-1]*FFC[J]-FDETA[J]*FFC[I-1])/XFC←
11.000 FETA[J] = F1[J]←
11.005 FDETA[J] = F2[J]←
6.030 REM RETURN←
```

APPENDIX E

The Fin-To-Tube Shape Factor

A closed-form integration for the view factor of the fin with respect to the tube was carried out by Mr. Yao. This view factor occurs in Eqs. 6.15 and 6.16. Only the final results are given here.

The reader should recognize that some of the symbols defined below (Eqs. D.1 through 6) apply only here.

Let (x_f, y_f, z_f) designate the position of the center of an area element A_f on the fin and z_m the same on the tube. Let r_e, s_t and s_r represent, respectively, the outer tube radius, the fin tip and the fin root thickness, and let the fin height be given as H.

Then, with

$$\rho = \sqrt{x_f^2 + y_f^2} \tag{D.1}$$

$$\beta = \text{arc tg } \frac{y_f}{x_f} \tag{D.2}$$

$$\alpha = \text{arc tg } \frac{s_r - s_t}{2r_c} \tag{D.3}$$

$$\phi = \text{arc tg } \frac{s_r}{2r_e} \tag{D.4}$$

$$a = \rho^2 + r_e^2 + (z_f - z_m)^2 \tag{D.5}$$

$$\phi^* = \text{arc sin } \frac{r_e}{\rho} \tag{D.6}$$

one obtains first

$$Z_1 = \ln \frac{a-2r_e \rho \cos(\phi^*-\beta)}{a-2r_e \rho \cos(\phi-\beta)} + \frac{a-2r_e^2 \cos(\alpha+\beta)}{a-2r_e \rho \cos(\phi^*-\beta)} - \frac{a-2r_e^2 \cos(\alpha+\beta)}{a-2r_e \rho \cos(\phi-\beta)} \tag{D.7}$$

$$Z_2 = \frac{8r_e^2 \rho^2 (z_t-z_m)^2 + 4\rho^2 r_e^2 a-a^3}{2(a^2-4r_e^2\rho^2)^{3/2}} \tag{D.8}$$

$$Z_3 = \text{arc sin } \frac{2r_e\rho-a \cos(\phi^*-\beta)}{a-2r_e\rho \cos(\phi^*-\beta)} - \text{arc sin } \frac{2r_e\rho-a \cos(\phi-\beta)}{a-2r_e\rho \cos(\phi-\beta)} \tag{D.9}$$

$$Z_4 = \frac{2a(z_f-z_m)^2 - a^2 + 4r_e^2\rho^2}{a^2 - 4r_e^2 \rho^2} \tag{D.10}$$

$$Z_5 = \frac{r_e\ \rho\ \sin(\phi^* - \beta)}{a - 2r_e\rho\ \cos(\phi^* - \beta)} - \frac{r_e\ \rho\ \sin(\phi - \beta)}{a - 2r_e\rho\ \cos(\phi - \beta)} \tag{D.11}$$

The final result is

$$SS = \Delta A_1\ \Delta z \left\{ \frac{-Z_1}{4\pi\rho} + \frac{\sin(\alpha+\beta)}{2\pi\rho} \left[\frac{\phi^* - \phi}{2} + Z_2 Z_3 Z_4 Z_5 \right] \right\} \tag{D.12}$$

This expression contains all the geometric relations that are required for fin-channel radiactive interaction. It needs to be evaluated only once for every fin element.

BIBLIOGRAPHY

. Schiller, Vortr. a.d. Geb. der Aerodynamik und verwandten Gebieten, Aachen, 1929.

. Nikuradse, Forschangsheft No. 256, VDI

. Techo, R., Tickner, R. R. and James, R. E., J. Applied Mech. Vol. 87, p. 443, June, 1965.

. El-Wakil, M. M., Nuclear Power Engineering, McGraw-Hill, 1962, p. 255.

Hausen, H. Z. VDI, Beihefte Verfahrenstechnik, 1943, p. 91.

Kreith, F., Principles of Heat Transfer, 2nd. ed., p. 128.

Hottel, H. C. and Sarofim, A. F. Radiative Transfer, McGraw-Hill, 1967.

Armaly, B. F. and Tien, C. L., A Note on the Radiative Exchange Among Nongray Surfaces, Tran. ASME, Vol. 92, Series C, No. 1, Feb. 1970, p. 178.

Guard, F. L. and Schultz, H. D., Space Shuttle Aerodynamic Heating Considerations, ASME Paper No. 70-HT/SpT-16, June, 1970.

Eckert, E.R.G., Survey on Heat Transfer at High Speeds, WADC Technical Report 54-70 USAF Wright-Patterson AFB, April, 1954.

Shapiro, A. H., The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol. II., Ronald Press, New York, 1953.

Milton, J. F. and Schramm, W. B., Space Shuttle Vehicle Concept and Technology Requirements ASME Paper No. 70-HT/SpT-21, June, 1970.

Wallace, R. R., Jr.; Vinson, J. R. and Kornhauser, M., Effects of Hypervelocity Particles on Shielded Structures, American Rocket Society Paper 1683-61, 1961.

Rodriguez, D., Meteoroid Shielding for Space Vehicles, Aerospace Engineering Vol. 19, No. 12, December, 1960.

Radiator Design for Space Vehicles, Publication MS-AP-0069, Garrett Corp., Airesearch Mfg. Co., Los Angeles, Calif.

Cosby, W. A. and Lyle, R. G., The Meteoroid Environment and Its Effects on Materials and Equipment, NASA SP-78, 1965.

Wright, C. C., Thermal Analysis and Meteoroid Protection of Space Radiators, Air Force Report No. SSD-TR-66-98, June, 1966.

8. NASA Space Vehicle Design Criterion [Environment] Meteoroid Environment Model - 1969 [Near Earth to Lunar Surface] NASA SP-8013, March, 1969.

9. Wulff, W. and Schipma, Design Guide for Pressurized Gas Systems, Task 7, NASA Contract No. NAS7-388, IITRI Report No. C6070-20, 1967.

0. U. S. Standard Atmosphere Supplements, 1966 U. S.Government Printing Office, Washington, D. C., 1966.

1. U. S. Standard Atmosphere, 1962., U. S. Government Printing Office, Washington, D. C., December, 1962.

2. Minzer, R. A., Champion, K.S.W. and Pond,H. L., The ARDC Model Atmosphere, 1959 AFCRC-TR-59-267, Air Force Cambridge Res. Center, August, 1959.

3. Keenan, J. H., and Kaye, J., Gas Tables, John Wiley and Sons, New York, 1945.

. Champion, K.S.W. and Minzner, R. A., Proposed Revision of U. S. Standard Atmosphere 90 to 700 km., AFCRL-62-802, Air Force Cambridge Res. Labs., July, 1962.

. Kopal, Z., Numerical Analysis, John Wiley and Sons, p. 195.

. Keller, B. K.,Numerical Methods for Two-Point Boundary-Value Problems.

. Tedd, Survey of Numerical Analysis, McGraw-Hill, 1962, p. 39.

STUDY OF DESIGN PARAMETERS OF SPACE BASE

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Part II: Space radiator simulation manual for computer code.

Part III: Space radiator simulation system analysis.

E-25-609

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GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering
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Final Report
Part I

SIMPLIFIED ANALYSIS AND OPTIMIZATION OF SPACE BASE AND SPACE SHUTTLE HEAT REJECTION SYSTEMS

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FOREWORD

This report covers part of the work performed during the second year phase of a two year research project, at the School of Mechanical Engineering at the Georgia Institute of Technology in Atlanta, Georgia, for the NASA Manned Spacecraft Center, Houston, Texas. The contract designation is NAS 9-10415 and the project title is "Study of Design Parameters of Space Base and Shuttle Heat Rejection Systems." The project was monitored by Dr. W.E. Simon of the Power Generation Branch of NASA MSC, Houston, Texas, and was performed by Dr. W.Z. Black and Dr. W. Wulff as Co-Investigators. The project resulted in one Annual Report [2]* and two Final Reports, the first one of which covers a detailed and rigorous space radiator simulation analysis [1] and includes a computer program users manual. The second Final Report is this report.

Although the study of system parameters and the system optimization were originally conceived to be performed on the basis of the rigorous radiator system simulation [1], the growing complexity of this simulation soon gave rise to the need for a simplified analysis. The simplified system simulation was later expanded into systematic optimization procedures. Both the simplified simulation and the optimization procedures serve to supplement and support the originally intended system parameter study [1].

The work presented here was supported by the contributions of computer coding by Mr. Richard J. Huntley and Mr. Wallace W. Carr, both Graduate Research Assistants and M.S. Candidates.

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*Numbers in brackets refer to the Bibliography at the end of this report.

SUMMARY

A simplified radiator system analysis was performed to predict steady-state radiator system performance. The system performance was found to be describable in terms of five non-dimensional system parameters. The governing differential equations are integrated numerically to yield the enthalpy rejection for the coolant fluid.

The simplified analysis was extended to produce firstly the derivatives of the coolant exit temperature with respect to the governing system parameters and secondly a procedure to find the optimum set of system parameters which yields the lowest possible coolant exit temperature for either a given projected area or a given total mass. The process can be inverted to yield either the minimum area or the minimum mass, together with the optimum geometry, for a specified heat rejection rate.

The major accomplishments of the simplified radiator system analysis are:

(1) the reduction of the number of necessary systems parameters from twelve or more to six,

(2) the graphical representation of system performance in terms of non-dimensional groups, suitable to aid in the design of radiative heat rejection systems, and

(3) an efficient computer code suitable for preliminary performance prediciton.

The accomplishments of the systematic optimization analysis are two computer codes which perform iterative optimizations processes leading to the maximum heat rejection for either a given projected fin-plus-tube area or a given total system mass.

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NOMENCLATURE

A^*	Normalized projected radiator area, Eq. 38
$\underset{\approx}{A}$	Coefficient matrix in Eq. 49
A_{ij}	Elements of coefficient matrix $\underset{\approx}{A}$
a_i	Coefficients of power polynomial
$B_{ij}=\partial^2\Theta_b/\partial x_i \partial x_j$	Second-order derivatives of Θ_b
c	Constant in Nusselt number relation, Eq. 35
c_p	Coolant fluid specific heat (Btu/(lbm R))
d	Tube diameter (ft)
$d^*=d/L_o$	Normalized tube diameter
F_{fs}	Fin to sink view factor, Eq. 15
f	Blockage coefficient, defined by Eq. 16
H	Fin height, from base to tip (ft)
$H^*=H/L_o$	Normalized fin height
$\bar{h}_c$	Average convective film coefficient for convection from fluid to tube (Btu/(hr ft^2 R))
i	Number of radiatively active sides
k	Thermal conductivity (Btu/(hr ft R)) of structural material
k_f	Thermal conductivity (Btu/(hr ft R)) of coolant fluid
L	Tube length (ft)
L_o	Reference length (ft), defined by Eq. 37
$L^*=L/L_o$	Normalized tube length
M	Parameter, defined by Eq. 12 (viewfactor augmentation)
M	Structural mass, per fin-tube element (lbm)
$M_o=\rho L_o^3$	Reference mass (lbm)

M_f	Coolant fluid mass (lbm)
$M^*=M/(M_o\phi_1)$	Normalized structural mass
$M_f^*=M_f/(M_o\phi_1)$	Normalized coolant mass
$M_{tot}^*=M_f^* + M^*$	Normalized total mass
m	Exponent on N_{Re} in Nusselt number relation, Eq. 35
$\dot{m}$	Coolant mass flow rate (lbm/hr)
N	Tube to sink view factor, Eq. 17
$N_c = \bar{N}_c\theta_b^3$	Conduction parameter, Eq. 14
$\bar{N}_c, N_c^*$	Reference conduction parameter, defined by Eqs. 20 and 58*
N_{Gr}, N_{Gr}^*	Graetz number, Eqs. 23 and 55
N_{Nu}, N_{Nu}^*	Nusselt number, Eqs. 8, 9, 10, 35 and 57*
N_{Pr}	Prandtl number, Eq. 7
N_{Re}, N_{Re}^*	Reynolds number, Eqs. 6 and 56*
n	Number of coolant channels
n	Exponent on N_{Pr} in Nusselt number relation, Eq. 35
p	Exponent on d/L-ratio in Nusselt number relation, Eq. 35
q"	Incident radiant heat flux (Btu/(hr ft^2))
r	Number of constraints
T	Absolute temperature (R)
t	Fin panel thickness (ft)
$t^* = t/L_o$	Normalized fin panel thickness
U	System parameter, defined by Eq. 22
V	System parameter, ratio of convective to radiative resistances Eq. 21
$\underset{\sim}{X}$	Vector whose components are the system parameters x_i

*Superscripted stars on symbol N indicate non-dimensional groups evaluated by replacing all dimensions L, H, d and t by L_o.

x_i	General system parameters, $x_1 = U$, $x_2 = V$, $x_3 = \bar{N}_c$, $x_4 = \lambda$
$\Delta \underset{\sim}{X}$	Computed changes of $\underset{\sim}{X}$, in iteration process
Y	Generalized distance from optimum, defined by Eqs. 49 and 50
y_i	Components of $\underset{\sim}{Y}$, defined by Eqs. 50
z	Distance along the tube (ft)

GREEK SYMBOLS

α_s	Solar absorptance
$\underset{\sim}{\delta}$	Incremental component vector defining a neighborhood about potential optimum, Eq. 47
ε	Surface emittance
$\zeta = Z/L_o$	Normalized axial distance
η	Effectiveness of unobstructed fin
$\bar{\eta}$	Combined fin and tube effectiveness
$\theta = T/T_o$	Normalized temperature
$\lambda = 4H/d$	
σ	Stefan Beltzmann constant $\sigma = 0.1714 \times 10^{-8}$ Btu/(hr ft^2 R^4)
μ	Dynamic viscosity (lbm/(sec ft))
ρ	Structural material density (lbm/ft^3)
ρ_f	Fluid density (lbm/ft^3)
ϕ_1	Parameter, defined by Eq. 42
ϕ_2	Parameter, defined by Eq. 44
ϕ_3	Parameter, defined by Eq. 63
φ_i	Constraints, Eqs. 39, 40, 41 and 46

SUBSCRIPTS

b	Fin base
c	Conduction

e	Channel exit
f	Fluid, bulk property
i,j	Component subscripts
k	Iteration step counting index
m	at optimum
s	sink
w	Fluid, at tube wall
o	Channel inlet

I. INTRODUCTION

A large-scale, complete and rigorous computer simulation of space radiator systems was developed under the same contract as the work presented here [1].* The computer code consists of over fifty program units and is capable of simulating transient as well as steady-state radiator system performances under prescribed time-dependent operational and environmental conditions. The program accommodates both gaseous and liquid coolant fluids with any consistently prescribed set of thermodynamic and transport properties. In principle, this large-scale computer program could serve to not only predict radiator system performance but also to optimize certain design paramters via enumeration of performance characteristics, associated with selected parameter combinations

Any large computer simulation must be tested during its development; the greater the number of independent verification modes the greater will be the confidence in the program performance. In addition to the tests described in Reference [1], a simplified radiator system analysis was developed to verify the large-scale computer program performance. This simplified analysis served later (1) to extend the rigorous analysis to a wider class of radiator geometries and operating conditions [1] than would have been possible otherwise and (2) to develop systematic optimization procedures in support of system parameter studies on the basis of the rigorous computer simulation.

The essence of the simplified analysis lies in the recognition of the dominant performance characteristics and in the parameter reduction through normalization of the governing differential equations. The optimization is based on standard requirements of extrema subject to suitable constraints. These requirements are imposed on the governing differential equations prior to their numerical integration.

Chapter II below is a discussion of the simplified analysis and is followed by the presentation of the optimization analysis in Chapter III.

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*Numbers in brackets refer to the Bibliography.

II. SIMPLIFIED RADIATOR SYSTEM ANALYSIS

A. Objective and Background

The purpose of this analysis is to provide an efficient process of least complexity which serves to describe the steady-state performance of a space radiator system. The radiator system is described in detail in the following chapter.

The analysis is intended to accommodate the essential features of the radiator system performance but to require less computational effort than the rigorous system simulation described in Reference [1]. Finally, the simplified analysis should serve as the basis for systematic optimization of the radiator system.

A first simplified analysis was developed during the first year of the contract period [2], also in support of the rigorous computer analysis, and for the purpose of treating approximately some radiator system geometries which deviate from the basic geometry underlying the rigorous system analysis, such as cylindrical shell radiator structures, asymmetrically loaded coolant channels etc. [1]. This analysis was based on two global energy balances, one for the coolant fluid and one for the radiator panel, and included the two thermal resistances associated with the energy transfer from the fluid to the tube and from the radiator into space. The mean tube wall temperature (and with it, the fin base temperature) was obtained from a single, transcendental equation (Eq. D.11, [2]) and the cooling capacity was found explicitly in terms of the mean tube wall temperature (Eq. 1.1 or 3, [2]). Agreement between this simplified analysis and the full-scale computer simulation was found to be approximately 4%.

The search for an optimum radiator geometry on the basis of the first simplified analysis lead to the conclusion that for optimum radiator geometries neighboring coolant channels should be expected to be close enough to each other so as to obstruct each other's, and the fin panel's, view of space. Moreover, the rigorous computer simulation indicated that the tube wall temperature changes significantly in the direction of the flow even though conduction parallel to the flow direction, both in the fluid, in the tube wall and in the fin, is negligible. These effects are not accounted for in the first simplified analysis.

The new simplified analysis presented here, for the prediction of steady-state radiator heat rejection performance, takes into account

(i) temperature variations within the fluid, tube and fin, along the direction of the flow,

(ii) temperature variation within the fin, normal to the direction of the flow,

(iii) direct radiative interaction between fin panel and space, tube and space, fin and tubes, tube and neighboring tubes (by approximation),

but does not take into account

(i) thermal conduction in the direction of the coolant flow, both in the fin-tube structure and the fluid

(ii) temperature variation of thermal properties,

(iii) end effects at the coolant fluid manifold,

(iv) cross-sectional changes in the fin panel,

(v) secondary reflections of radiant heat.

The analysis reduces to an initial value problem consisting of two ordinary, first-order, coupled differential equations, with one of its initial conditions given through a transcendental equation. The new formulation is suitable for optimization.

B. Description of Radiator System

The radiator system considered here consists of a given number of parallel coolant channels, equally spaced in one plane, and connected by rectangular fin panels which have constant thickness and are symmetric with respect to the plane through the tube areas.

The coolant channels are taken to be thin-walled tubes of circular cross-section, with diameter d and length L. Substitution of the hydraulic diameter for the diameter permits readily the inclusion of channels with non-circular cross-sections, except for possible effects from radiative interaction between tube, fin and environment.

Let the distance between tube centers be designated by $d + 2H$ and the fin panel thickness by t. Then the radiator can be considered to consist of the given number n of identical fin elements as shown in Figure 1.

The coolant fluid enters the channel at $z = 0$ with time-invariant temperature $T_f = T_o$. Both the fluid temperature $T_f(z)$ and the fin base temperature $T_b(z)$ decrease along the tube provided the equivalent sink temperature T_s is less than T_o. The coolant fluid emerges from the radiator at $z = L$ with the exit temperature T_e.

The objective of the analysis is to predict the rate of heat rejection $\dot{m}\, c_p\, (T_o - T_e)$ per tube for a given mass flow rate $\dot{m}$ per tube and given fluid properties, namely density ρ, specific heat c_p, thermal conductivity k_f, dynamic viscosity μ, and given properties of the fin, that is, surface emittance ϵ, solar absorptance α_s, and thermal conductivity k.

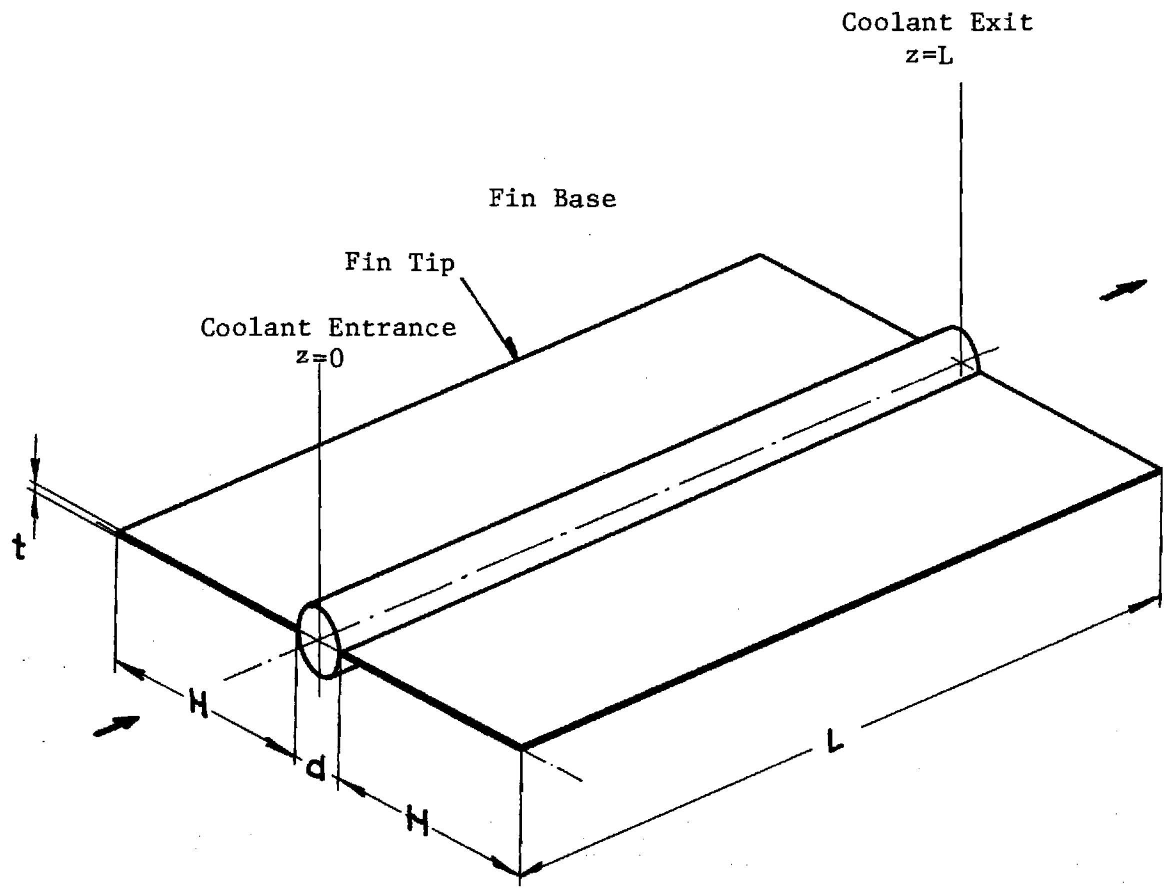

Figure 1.   Geometry of Fin System Element

C. Governing Equations

1. Conservation of Energy

Setting the local change of the fluid enthalpy flux first equal to the local heat exchange per unit tube length between fluid and tube wall, and then equal to the radiative heat rejection per unit tube length one obtains, for i effective sides of the radiator:

$$-\dot{m}\, c_p \frac{dT_f}{dz} = \pi d \bar{h}_c (T_f - T_b) \tag{1}$$

$$\pi d \bar{h}_c (T_f - T_b) = 2iH\varepsilon\sigma\bar{\eta}(T_b^4 - T_s^4) \tag{2}$$

where $\bar{h}_c$ and σ represent, respectively, the convective film coefficient and the Stefan-Boltzmann constant. The symbol $\bar{\eta}$ represents the overall tube-and-fin effectiveness and is evaluated in Section 3. The convective film coefficient is computed from the Nusselt number N_{Nu}

$$\bar{h}_c = N_{Nu} \frac{k_f}{d} \tag{3}$$

the evaluation of which is deferred to Section 2. The equivalent sink temperature T_s is computed from the known incident normal radiant heat flux q'' by

$$T_s = \sqrt[4]{\frac{\alpha_s}{\varepsilon} \frac{q''}{\sigma}} \tag{4}$$

The first-order differential equation, Eq. 1, is subject to the initial condition at z = 0

$$T_f(0) = T_o \tag{5}$$

Equations 1 and 2 determine the two dependent variables $T_f(z)$ and $T_b(z)$. Integration of Eq. 1 from $z = 0$ to $z = L$ gives the unknown fluid exit temperature T_e.

2. Convective Film Coefficient

The Nusselt number N_{Nu} in Eq. 3 depends on the Reynolds number N_{Re}, the Prandtl number N_{Pr} and the d/L ratio.

$$N_{Re} = \frac{4\dot{m}}{\pi d \mu} \tag{6}$$

$$N_{Pr} = \frac{\mu c_p}{k_f} \tag{7}$$

For laminar flow, $N_{Re} \leq 2300$, of non-metallic fluids, $N_{Pr} \geq 0.1$, Hausen [3] established the relation

$$N_{Nu} = \left[3.65 + \frac{0.0668\, N_{Re} N_{Pr} \frac{d}{L}}{1 + 0.045 (N_{Re} N_{Pr} \frac{d}{L})^{2/3}} \right] \left(\frac{\mu_f}{\mu_w} \right)^{0.14} \tag{8}$$

The nomogram in Figure 2, taken from the VDI Waermeatlas,* facilitates the estimate of the Nusselt number in accordance with Eq. 8.

For turbulent flow, $N_{Re} > 2300$, of non-metallic fluids, $N_{Pr} \geq 0.1$, similarity considerations lead to

$$N_{Nu} = 0.116 \left[1 + \left(\frac{d}{L} \right)^{2/3} \right] (N_{Re}{}^{2/3} - 125) N_{Pr}{}^{1/3} \left(\frac{\mu_f}{\mu_w} \right)^{0.14} \tag{9}$$

which is also presented in a nomogram in Figure 3.

Liquid metal convective heat transfer in tubes, $N_{Pr} < 0.1$, may be represented by the result of the work by Seban and Shimazaki [4] which is

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*VDI-Verlag GMBH, Düsseldorf, West Germany valid for $(N_{Re}\ N_{Pr}) > 100$ and $L/d > 60$

$$N_{Nu} = 5.0 + 0.025\ (N_{Re} N_{Pr})^{0.8} \qquad (10)$$

Other Nusselt number relationships may be more suitable in a particular case. Their selection does not affect the ensuing analysis because the Nusselt number calculation is part of the input data preparation, prior to the numerical evaluation of the solution.

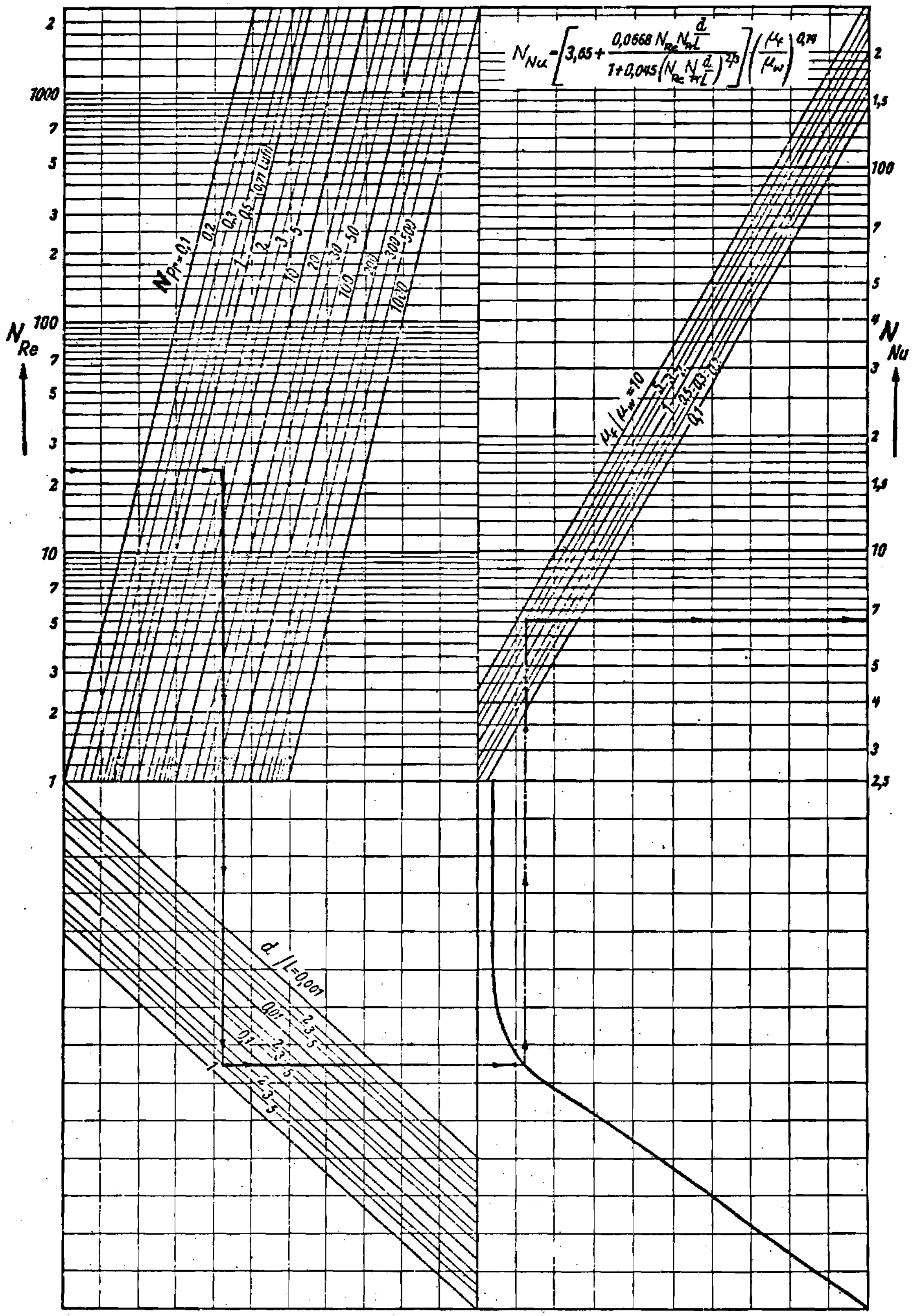

Figure 2. Nussett Number Nomogram for Laminar Flow of Non-Metallic Coolant Fluids, Eq. 8. (VDI Waermeatlas)

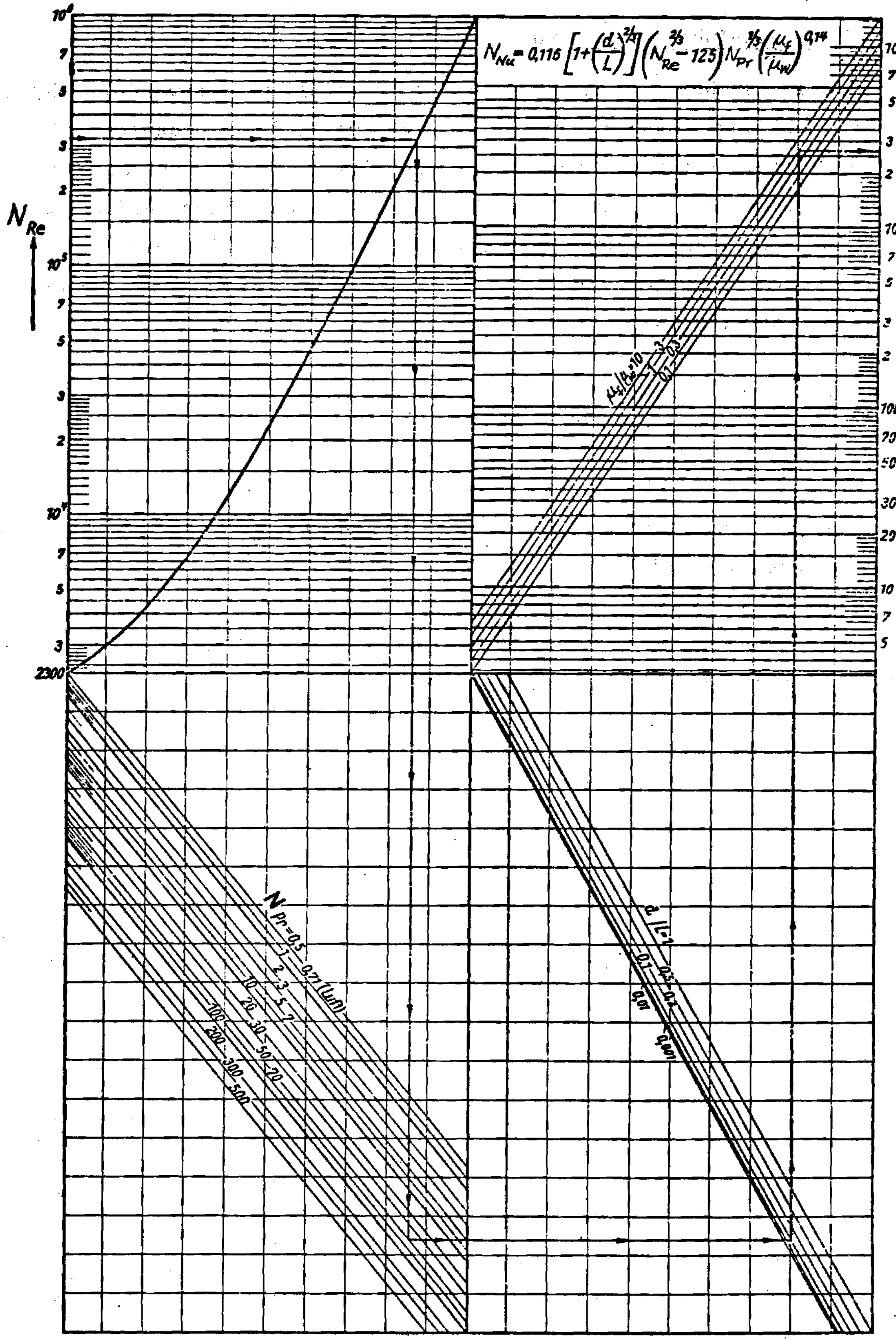

Figure 3. Nussett Number Nomogram for Turbulent Flow of Non-Metallic Coolant Fluids, Eq. 9. (VDI Waermeatlas)

3. Total Fin-Tube Effectiveness

The symbol $\bar{\eta}$ in Eq. 2 denotes the overall radiative fin-and-tube effectiveness and accounts not only for the non-uniform temperature distribution within the fin and normal to the flow direction, but also for the effects on the radiative heat transfer from the tube. These effects are due to the additional radiating tube area and the partial blockage of emission from the fin and the tubes by the tubes of the neighboring fin elements. Adding the contributions from the tube to that of the fin, one obtains

$$\bar{\eta}(z) = M(z) \cdot \eta(z) + N \tag{11}$$

Here, $\eta(z)$ is the radiative fin effectiveness of the unobstructed fin, Eqs. 32, [5,6,7] and varies with the fin base temperature $T_b(z)$. The factor M is the product of the shape factor of the fin with respect to the sink, F_{fs}, and the corrective term f on η for the temperature profile distortion resulting from the tube-fin interaction [8]:

$$M = F_{fs}(\lambda) \cdot f(\lambda, N_c) \tag{12}$$

where

$$\lambda = \frac{4H}{d} \tag{13}$$

and

$$N_c = \frac{2\varepsilon\sigma H^2}{kt} \quad [T_b(z)]^3 \tag{14}$$

which is the well-known conduction parameter. Hottel's crossed-string method yields

$$F_{fs}(\lambda) = \left(\sqrt{\lambda(\lambda + 2)} + \arcsin \frac{1}{1 + \lambda} - \pi/2 \right) / \lambda \tag{15}$$

and the curve fit of data in Reference [8] resulted in

$$f(\lambda, N_c) = 1 - (N_c/\lambda)(0.1460\ N_c - 0.02866)\ . \tag{16}$$

Finally, the symbol N in Eq. 11 represents the radiative heat rejection contributed by the tubes and is the shape factor of the tube with respect to the sink, multiplied by the tube-to-fin area ratio

$$N(\lambda) = \pi \left[1/2 + \left[\lambda + 2 - \sqrt{\lambda(\lambda + 2)} - \arcsin \frac{1}{\lambda + 1} \right] / \pi \right] / \lambda \tag{17}$$

This completes the description of the overall fin-and-tube effectiveness. In summary it should be emphasized that axial conduction, radial tube wall temperature variation, kinetic and potential coolant energies, and end effects are ignored, that radiative interaction between tube and fin and between tubes is only approximate and that the representation of Eq. 16 is limited to $T_s < 0.8\ T_b$ (but could be extended, in principle).

D. Scaling Parameters

Effective analysis, numerical integration, graphical representation of numerical results and, ultimately, the system optimization makes the reduction of parameters mandatory. Introduce the non-dimensional

axial distance $$\zeta = \frac{z}{L} \tag{18}$$

temperature $$\theta = T/T_o \tag{19}$$

reference conduction parameter $$\bar{N}_c = \frac{2\varepsilon\sigma T_o^3 H^2}{kt} \tag{20}$$

ratio of convective to radiative resistance $$V = \frac{1}{\pi}\frac{t}{H}\frac{k}{k_f}\frac{\bar{N}_c}{N_{Nu}} \tag{21}$$

convection number $$U = \pi N_{Nu}/N_{Gz} \tag{22}$$

where the Graetz number N_{Gz} is defined by

$$N_{Gz} = (c_p\,\dot{m})/(k_f L) = \frac{\pi}{4}\frac{d}{L} N_{Re}\, N_{Pr}\ . \tag{23}$$

With these parameters and the λ defined by Eq. 13 one may recast the problem as previously established by Eqs. 1,2 and 5 as given by Eqs. 24 through 26:

$$\frac{d\theta_f}{d\zeta} = -\,U(\theta_f - \theta_b) \tag{24}$$

$$\theta_f - \theta_b = V\bar{\eta}(\theta_b^4 - \theta_s^4) \tag{25}$$

subject to the initial condition at $\zeta = 0$

$$\theta_f(0) = 1 \ . \tag{26}$$

Integration of Eq. 24 subject to Eqs. 25 and 26 yields the coolant fluid exit temperature θ_e sought

$$\theta_e = \theta_f(1) \tag{27}$$

and, consequently, this coolant fluid exit temperature is a function of five parameters

$$\theta_e = \theta_e(U,V,\bar{N}_c,\lambda;\theta_s) \ . \tag{28}$$

The first four parameters correspond to the geometrical dimensions L, H, t and d of the radiator system and θ_s represents the environment.

E. Solution

Equation 25 is transcendental because of $\bar{\eta}(\theta_b)$ and would require iterative solutions at every step of the numerical integration of Eq. 24. It is more economical to derive a second differential equation for θ_b by differentiating Eq. 25

$$\frac{d\theta_b}{d\zeta} = \frac{-U}{\dfrac{1}{\theta_f - \theta_b} + \dfrac{1}{\bar{\eta}}\dfrac{d\bar{\eta}}{d\theta_b} + \dfrac{4\theta_b^{\,3}}{\theta_b^{\,4} - \theta_s^{\,4}}} \tag{29}$$

and to obtain the initial condition for Eq. 29 through a single iterative process (Newton Raphson method) from

$$V\bar{\eta}(\theta_b^{\,4} - \theta_s^{\,4}) + \theta_b = 1 \quad \text{at} \quad \zeta = 0 \tag{30}$$

• The derivative $d\bar{\eta}/d\theta_b$ is obtained from Eqs. 11 and 16

$$\frac{d\bar{\eta}}{d\theta_b} = \frac{d\bar{\eta}}{dN_c}\frac{dN_c}{d\theta_b} = 3\,\bar{N}_c\theta_b^{\,2}\,\frac{\partial}{\partial N_c}(M\eta)$$

$$= 3\bar{N}_c\theta_b^{\,2}\left\{\eta F_{fs}\left[0.02866 - 0.2920\,\bar{N}_c\theta_b^{\,3}\right]/\lambda + M\frac{d\eta}{dN_c}\right\} \tag{31}$$

which can be evaluated once the fin effectiveness $\eta(N_c)$, that is the ratio of the actual power loss from an unobstructed (tubless) fin panel to the power loss from an ideal, unobstructed fin of infinite thermal conductivity, is represented by a power polynomial:

$$\eta(N_c) = \sum_{i=0}^{6} a_i (N_c)^i \tag{32a}$$

where

$a_0 = 1.000\ 000$

$a_1 = -1.163\ 143$

$a_2 = 1.478\ 836$

$a_3 = -1.267\ 550$

$a_4 = 0.632\ 522\ 3$

$a_5 = -0.162\ 706\ 7$

$a_6 = 0.016\ 542\ 23$

Equation 32 is valid for $0 \leq N_c \leq 2.5$. For greater values, $N_c > 2.5$

$$\eta(N_c) = 0.686\ 609\ 5\ e^{-\ 0.229\ 771\ 8} \tag{32b}$$

Equations 24 and 29 have been integrated by a fourth-order Runge-Kutta procedure [2], subject to initial conditions given by Eqs. 26 and 30. The result of the integration yields primarily Θ_e in the form of Eq. 28.

F. Results

A typical computer print-out of the results is shown in Figure 4. First are presented the five parameters $\{\theta_s; U, V, \bar{N}_c, \lambda\}$ of Eq. 28, as read-in. Following that is a table in which are listed, as functions of axial distance measured from the coolant fluid inlet, the fluid temperature θ_f = THETAF, the fin base temperature θ_b = THETAB, next the local conduction parameter N_c = NC, the local total fin-plus-tube effectiveness $\bar{\eta}$ = ETABAR, the local fin effectiveness η = ETA, the nondimensional axial position ζ = ZETA and, finally, the number of integration steps required to reach the particular axial position. The number of integration steps depends on the chosen error limits and the rates of variable changes.

The time rate of heat rejection per fin element (tube) is to be computed from

$$\dot{m}\, c_p\, (T_o - T_e) = \dot{m}\, c_p\, T_o\, (1 - \theta_e) \tag{32}$$

Parameter studies are presented in Figures 5 through 9. The non-dimensional fluid exit temperature is plotted versus non-dimensional fin panel area with the temperature θ_s (Fig. 5), the non-dimensional tube spacing λ (Figs. 6 and 7) and the reference conduction parameter $\bar{N}_c$ (Figs. 8 and 9) as parameters.

THETA-S =	.800000
U =	.100000+01
V =	.200000+01
FNCBAR =	.200000+00
LAMBDA =	.250000+02

THETAF	THETAB	NC	ETABAR	ETA	ZETA	STEP NO
1.000000	.838159	.117763	.964240	.881541	.00	1
.984460	.835315	.116568	.965251	.882615	.10	2
.970137	.832677	.115468	.966185	.883569	.20	4
.956937	.830231	.114453	.967048	.884452	.30	5
.944763	.827964	.113518	.967846	.885267	.40	6
.933557	.825862	.112656	.968583	.886020	.50	7
.923266	.823916	.111861	.969263	.886716	.60	8
.913669	.822113	.111128	.969892	.887359	.70	9
.904875	.820443	.110453	.970473	.887953	.80	10
.896764	.818898	.109830	.971009	.888501	.90	11
.889284	.817467	.109255	.971505	.889008	1.00	12

FIGURE 4. TYPICAL COMPUTER PRINT-OUT FOR RADIATOR SYSTEM PERFORMANCE

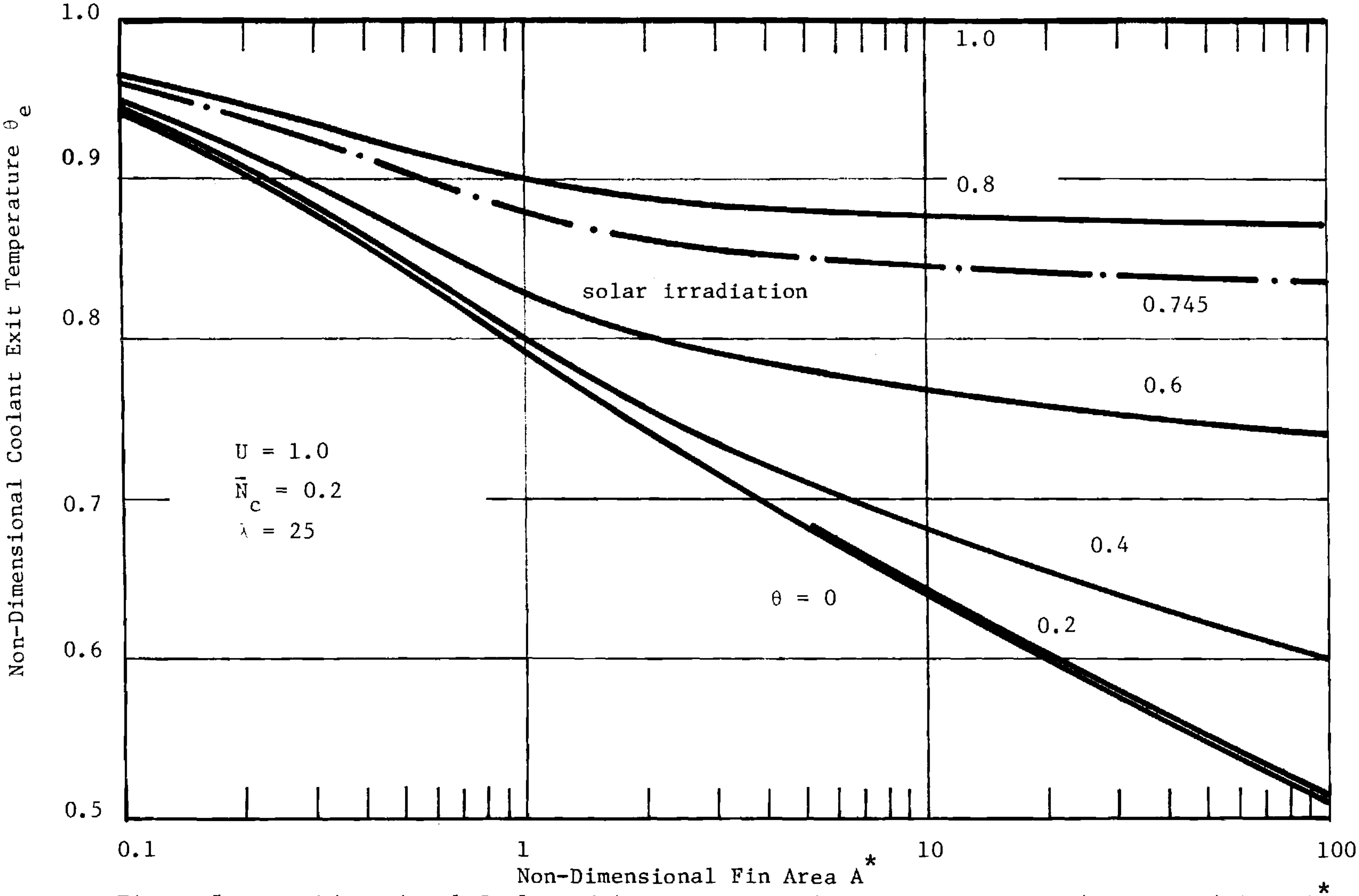

Figure 5. Non-Dimensional Coolant Exit Temperature θ vs. Non-Dimensional Fin Panel Area A^* with Sink Temperature θ_s As Parameter.

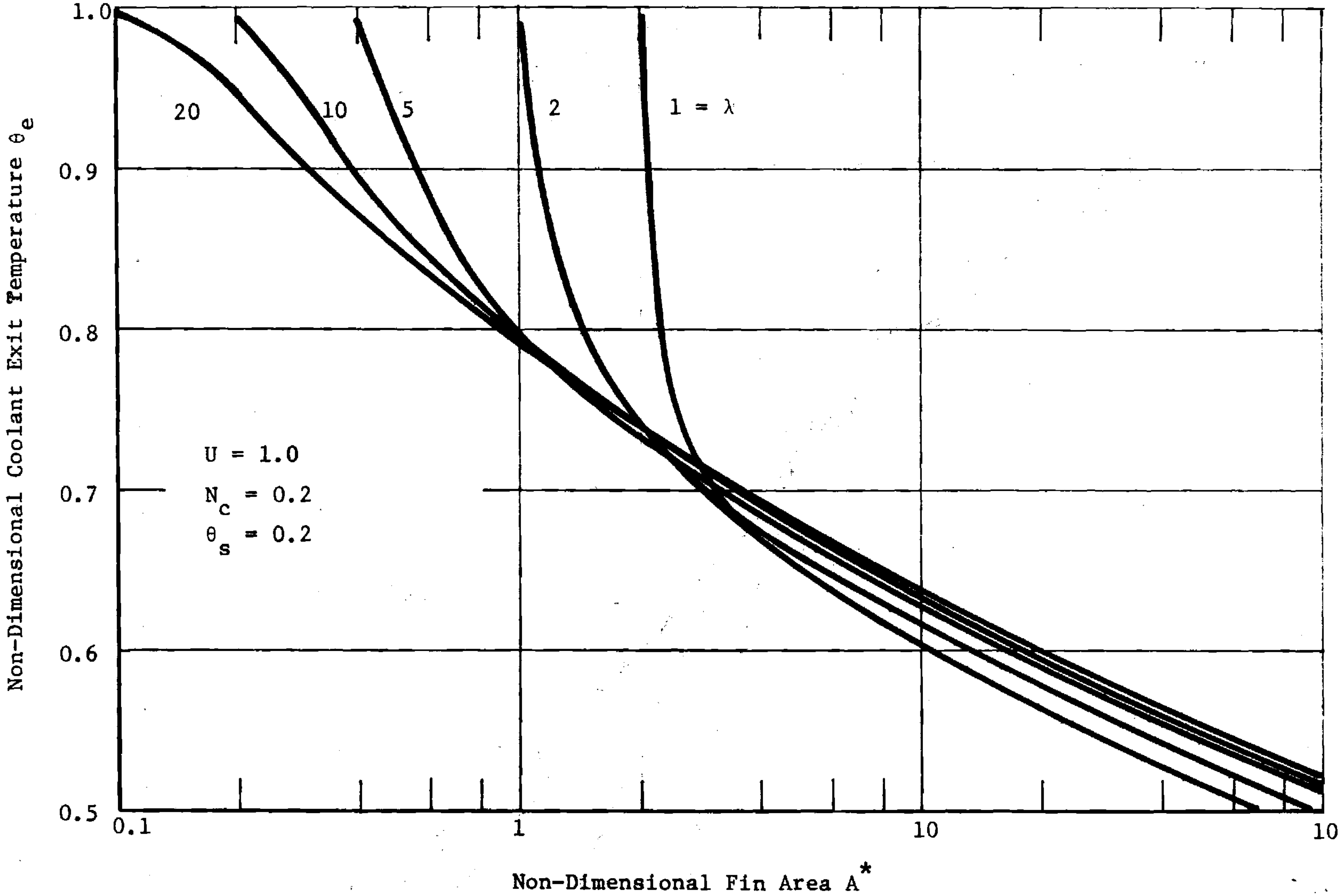

Figure 6. Non-Dimenstional Coolant Exit Temperature vs. Non-Dimensional Fin Area For Constant U and Varying λ

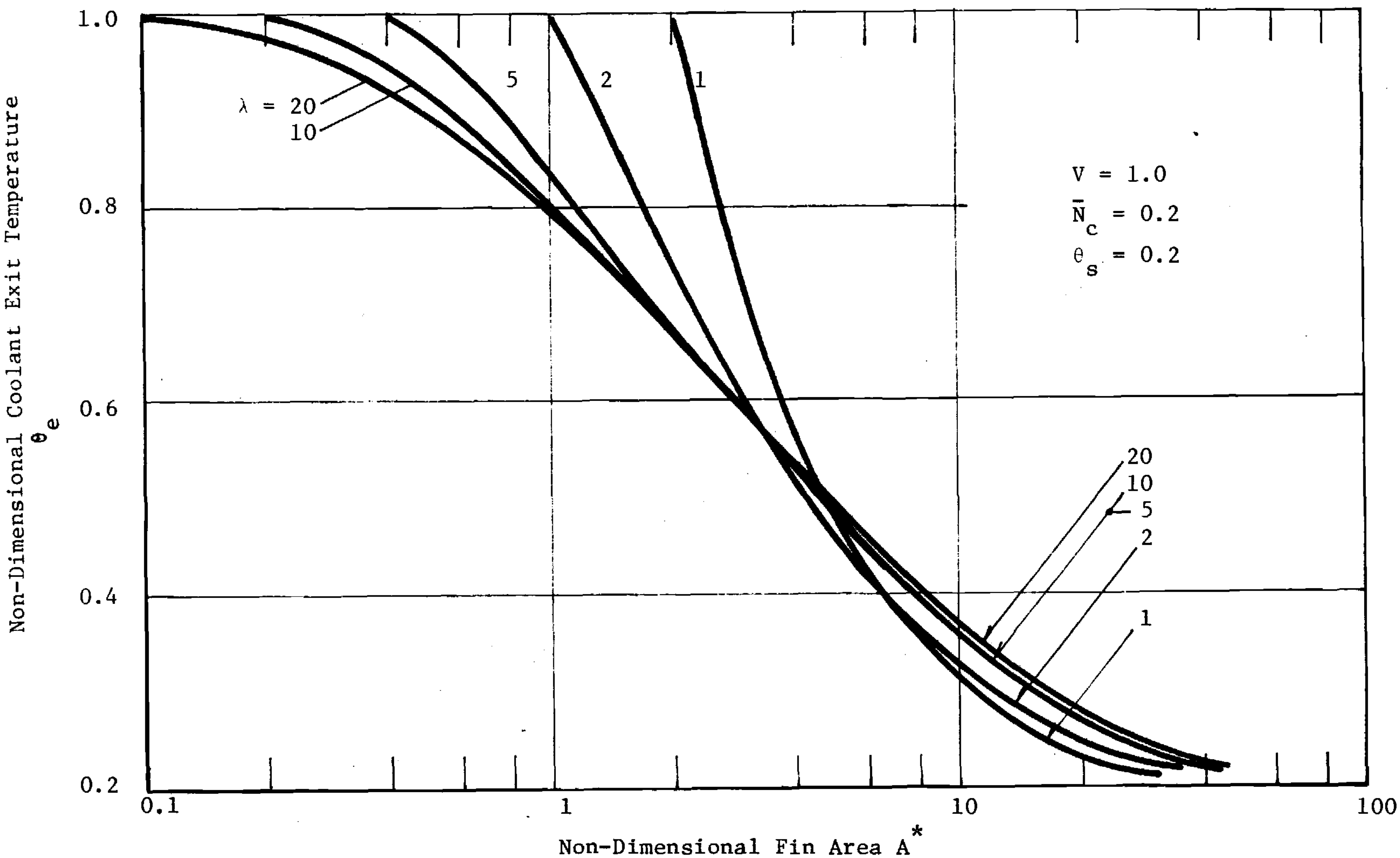

Figure 7. Non-Dimensional Coolant Exit Temperature vs. Non-Dimenstional Fin Area For Constant V and Varying λ

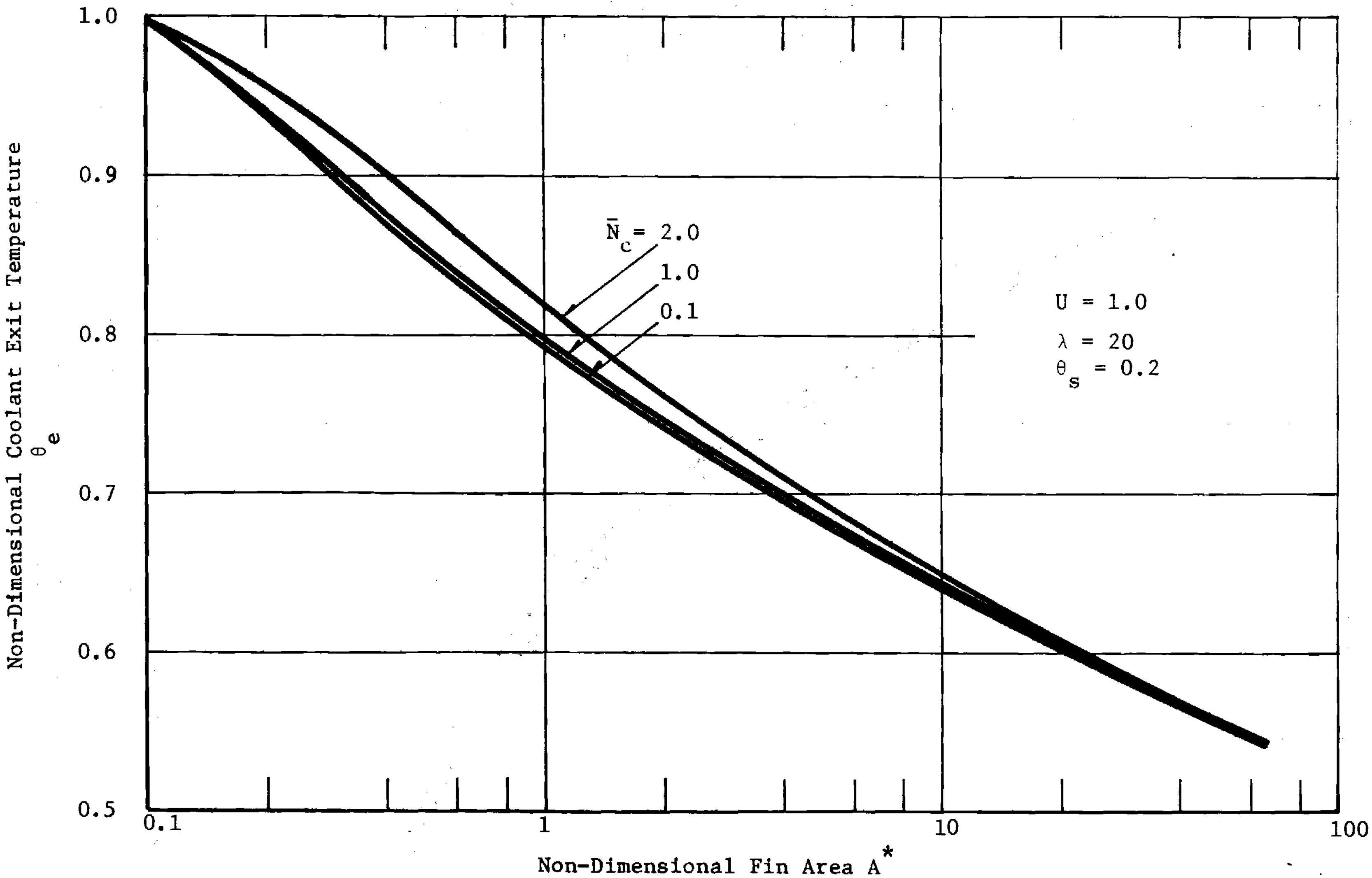

Figure 8. Non-Dimensional Coolant Exit Temperature VS. Non-Dimensional Fin Area For Varying Conduction Parameter and Long Fins.

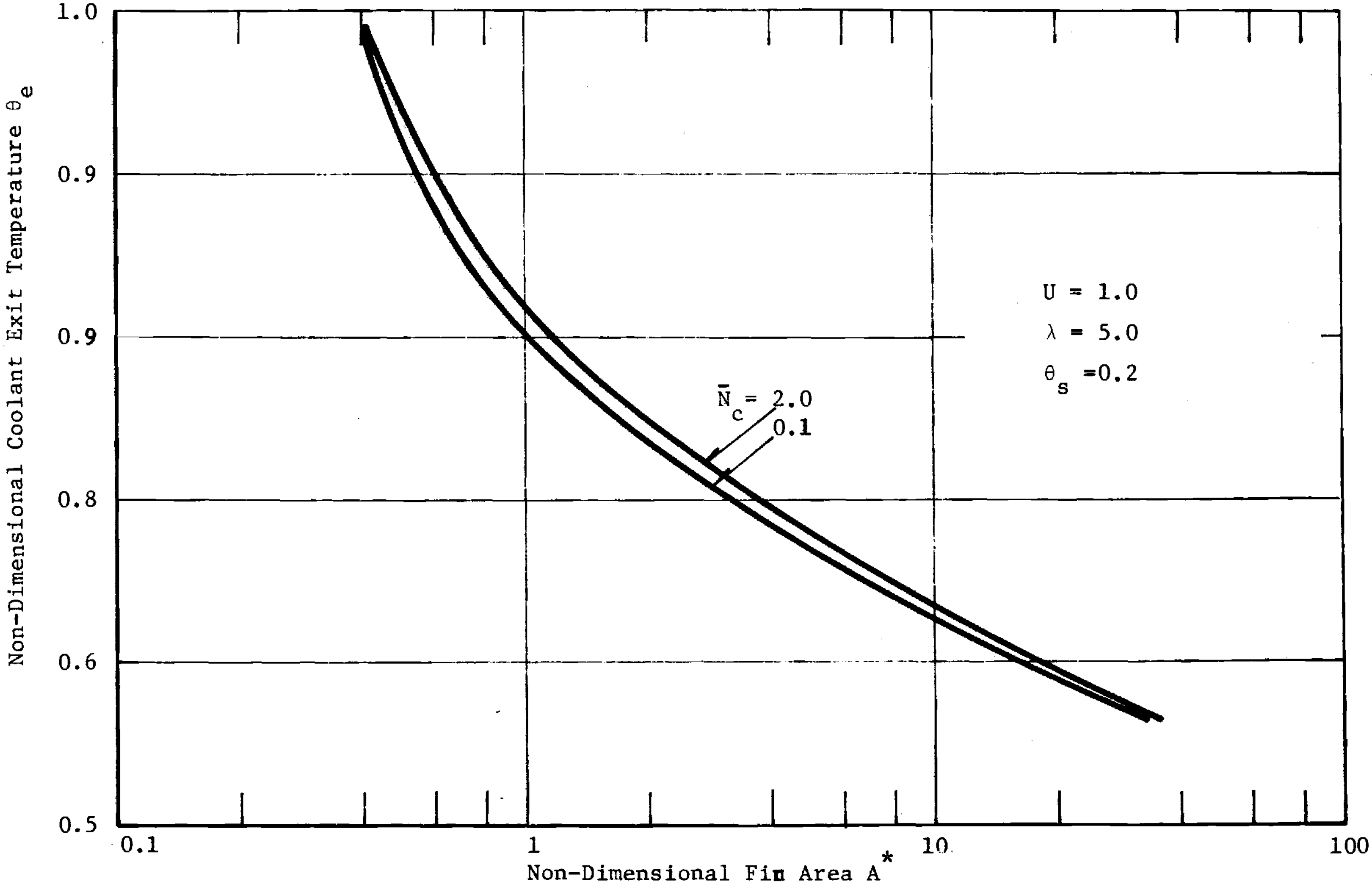

Figure 9. Non-Dimensional Coolant Exit Temperature VS. Non-Dimensional Fin Area For Varying Conduction Parameter and Short Fins

III. OPTIMIZATION OF THE RADIATOR SYSTEM

A. Purpose

In the design of the radiator system all parameters describing the system objectives and the system environment are prescribed beforehand while, at some occasions and within certain limits, the geometry of the system may be selected in the process of the design. This possible freedom of choice leads to the optimization of the radiator system geometry.

The primary purpose of the radiator system is to lower the coolant fluid temperature. For a given set of constraints the radiator with the lowest fluid exit temperature is considered here to be an optimum radiator system.

The set of constraints to be imposed on the optimum radiator system must be selected for a particular set of circumstances. In this analysis two sets out of many possible constraints were selected, that is, weight (or volume) and projected area of the radiator are considered to be prescribed.

The process of optimization proposed here, namely to find the minimum coolant fluid exit temperature for either a fixed radiator area or a fixed mass may be inverted to yield the minimum radiator area or weight for a prescribed cooling rate.

The optimization process can be outlined in the following steps:

(i) select, for given coolant exit temperature

$$\theta_e = \theta_e \{U, V, \bar{N}_c, \lambda;\ \theta_s\} \tag{28}$$

that optimum set $\{U, V, \bar{N}_c, \lambda\}$ of geometric parameters which constitutes, under selected constraints, the system geometry for the lowest possible coolant exit temperature,

(ii) transform the non-dimensional groups U, V and $\bar{N}_c$ into suitable, non-dimensional radiator length L^*, fin height H^* and panel thickness t^*,

(iii) calculate the physical dimensions L, H, t and d of the optimum radiator system.

If all fin elements operate under optimum conditions then the radiator as a whole operates under optimum conditions.

B. Problem Formulation

1. General

Of the five parameters U, V, $\bar{N}_c$, λ and θ_s which define θ_e only the first four can be considered independent while θ_s is determined by the incident radiant flux. For simplicity let us introduce the vector $\underset{\sim}{X}$ with components $x_1 = U$, $x_2 = V$, $x_3 = \bar{N}_c$ and $x_4 = \lambda$. The minimum coolant fluid exit temperature $\theta_e(\underset{\sim}{X})$, subject to $r \leq 3$ constraints may be obtained from the necessary conditions for a relative extremum

$$\frac{\partial\theta_e}{\partial x_i} = 0 \qquad i = 1, \ldots, (4 - r) \tag{33}$$

and the r constraints

$$\varphi_j(\underset{\sim}{X}) = 0 \qquad j = i, \ldots, r \; . \tag{34}$$

This problem formulation implies that the r constraint equations can be solved explicitly for r components of $\underset{\sim}{X}$ which can be substituted into Eqs. 33 to yield (4 - r) equations for the remaining (4 - r) components. This was in effect achieved by replacing the Nusselt number relationships given in Eqs. 8 and 9 by a simpler relation of the form

$$N_{Nu} = c\; N_{Re}{}^{m}\; N_{Pr}{}^{n}\; (d/L)^{p} \tag{35}$$

with appropriate constants c = 0.023, m = 0.8, n = 1/3, p = 0, for $N_{Re} \geq 2{,}300$; and c = 1.86, m = n = p = 1/3 for $N_{Re} < 2{,}300$. The method of Lagrangian multipliers, however, permits the retention of the original constraints at the expense of additional, computational efforts in the case of fixed-mass constraints, since Eqs. 34 need not to be solved explicitely for $\underset{\sim}{X}$.

Two sets of constraints have been considered. Both sets have in common four sets of bounds

$$\left.\begin{aligned}
U_{min} &\le x_1 \le U_{max} \\
V_{min} &\le x_2 \le V_{max} \\
(\bar{N}_c)_{min} &\le x_3 \le (\bar{N}_c)_{max} \\
\lambda_{min} &\le x_4 \le \lambda_{max}
\end{aligned}\right\} \qquad (36)$$

which represent practical limits of the design parameters x_i, $i = 1, \ldots, 4$. Should the search procedure lead to the intersection of any of the above limits, then their appropriate equalities would enter the set of constraints. The other two constraints, namely of fixed volume or of fixed area, are discussed below.

2. Area Constraint

Introduce the characteristic length of a single fin element

$$L_o = \sqrt{\frac{\dot{m}\, c_p}{i\varepsilon\sigma T_o^3}} \tag{37}$$

which may be interpreted as the length of a square fin element whose effectiveness is unity and which reduces the fluid temperature to zero. Dividing the physical dimensions L, H, t and d by the reference length L_o one obtains the non-dimensional geometric quantities L^*, H^*, t^* and d^*, respectively. The normalized projected fin element area is (for t <<d)

$$A^* = A/L_o^2 = [2HL + dL]/L_o^2 \quad . \tag{38}$$

Consequently, the constraint of "fixed area," the first of Eq. 34, becomes

$$\varphi_1 = 2H^*L^*[1 + 2/\lambda] - A^* = 0 \tag{39}$$

or

$$\varphi_1(x_1,x_2,x_4) = x_1x_2(1 + 2/x_4) - A^* = 0 \tag{40}$$

This constraint equation can be solved explicitly for any one of its arguments, regardless of applicable Nusselt number relationship (see comments following Eq. 34).

The constant area constraint may be supplemented by an additional constraint reflecting the preference for a particular fin panel thickness, arising from manufacturing considerations. A fixed panel thickness t, or equivalently t^* would require

$$\varphi_2(\underset{\sim}{X}) = t^* - \phi_1 x_2^2/x_3 \cdot N_{Nu}^2\,(\underset{\sim}{X}) = 0 \tag{41}$$

where ϕ_1 is known beforehand

$$\phi_1 = (1/2i)\ (\pi k_f/k)^2\ k^2/(i\dot{m}\ C_p\ \epsilon\,\sigma\,T_o^{\ 3}) \qquad (42)$$

Equation 41 depends on the Nusselt number relationship used. It becomes a necessary constraint when the optimization tends toward panel thicknesses which approach the tube diameter.

3. Volume Constraint

The volume constraint is stipulated by the desire to design a radiator system of minimum mass. The coolant mass may (liquids) or may not (gases) contribute significantly to the total mass.

The mass of one fin element is, under the assumption of a tube wall thickness, equal to the fin panel thickness

$$M^* = \frac{M}{\phi_1 M_o} = L^* t^* \, [2H^* + \pi(d^* - t^*)] \simeq \frac{UV^3}{\bar{N}_c} \left[1 + \frac{2\pi}{\lambda}\right] N_{Nu}^2 \qquad (43)$$

provided $t^* << d^*$. Here $M_o = \rho L_o^3$ is the reference mass and M the physical mass of the structure. With

$$\phi_2 = 2i(\rho_f/\rho)(k/k_f) \qquad (44)$$

the coolant fluid mass may be expressed as

$$M_f^* = \frac{M_f}{\phi_1 M_o} = \phi_2 \, N_{Nu} \left(\frac{V}{\lambda}\right)^2 U \quad . \qquad (45)$$

Consequently, the "volume constraint" becomes

$$\varphi_1(\underset{\sim}{X}) = M_{tot}^* - x_1 x_2^2 \, N_{Nu}(\underset{\sim}{X}) \left\{ x_2 \, [1 + 2\pi/x_4] N_{Nu}/x_3 + \phi_2/x_4^2 \right\} = 0 \qquad (46)$$

where $M_{tot}^* = M^* + M_f^*$. Equation 46 reveals that while $\phi_2 > 1$ the fluid mass contributes to the total mass only when x_4 becomes small. For the expected cases of $x_4 \approx 10$ Eq. 46 reduces to a volume constraint as the influence of the density ratio ρ/ρ_f vanishes.

4. Sufficiency Requirements

An optimum radiator is found at $\underset{\sim}{X}_m$ when $\theta_e(\underset{\sim}{X}_m)$ is a minimum, that is, when in the vicinity of $\underset{\sim}{X}_m$

$$\theta_e(\underset{\sim}{X}_m + \underset{\sim}{\delta}) > \theta_e(\underset{\sim}{X}_m) \qquad (47)$$

where $\underset{\sim}{\delta}$ is a small vector, with components $\{\Delta x_1, \ldots, \Delta x_4\}$, and with its endpoint on the hypersurface defined by Eqs. 34.

There exist analytical expressions for the sufficiency conditions in terms of second-order derivatives $\partial^2\theta_e/\partial x_i \partial x_j$ which are applicable when either all constraints can be solved explicitly as implied by Eqs. 33 and 34 or the number of constraints is at least two. Since, however, θ_e is obtained through numerical integration of Eqs. 24 and 29 and the sufficiency test is to be performed only once the potential optimum is found, it appears economical to evaluate Eq. 47 directly. Further developments concerning the sufficiency criteria are necessary at this time.

C. Solution

1. The Optimum

The remaining task is to solve the system of Eqs. 33 as they are obtained after substitution of Eqs. 34. The solution is obtained through an iterative process based on the Newton-Raphson procedure. Starting with an estimated set of parameters $\underset{\sim}{X}_1$ the iteration is carried on according to

$$\underset{\sim}{X}_{k+1} = \underset{\sim}{X}_k + \Delta\underset{\sim}{X}_k \ , \ k = 1,2, \ldots \tag{48}$$

where $\underset{\sim}{X}_k$ represents the current, $\underset{\sim}{X}_{k+1}$ the future parameter set and the increments $\Delta\underset{\sim}{X}_k$ are the solution to the system of linear algebraic equations

$$\underset{\sim}{Y}_k = (\underset{\sim}{A})_k(\Delta\underset{\sim}{X})_k \ . \tag{49}$$

The current components $(y_i)_k$ of $\underset{\sim}{Y}_k$ are the current values of the derivatives

$$y_i = -\frac{\partial\theta_e}{\partial x_i} \ , \ i = 1, \ldots, (4 - r) \ . \tag{50}$$

The current elements $\{A_{ij}\}_k$ of the square matrix $(\underset{\sim}{A})_k$ are the second-order derivatives

$$A_{ij} = \frac{\partial^2\theta_e}{\partial x_i \partial x_j} \ ; \ i,j = 1, \ldots, (4 - r) \ . \tag{51}$$

It is obvious that the matrix A_{ij} is symmetric and one needs to compute only $(5 - r)(4 - r)/2$ independent, second-order derivatives.

The derivatives in Eq. 50 and 51 are obtained from Eqs. 24 and 25 by first differentiating with respect to x_i, $i = 1, \ldots, (4 - r)$ and then interchanging the order of differentiation. This leads first to $2(4 - r)$ first-order, ordinary, non-linear differential equations for

$$
\left.\begin{aligned}
-\frac{dy_i}{d\zeta} &= \frac{d}{d\zeta}\left(\frac{\partial\theta_f}{\partial x_i}\right), \quad i = 1, \ldots, (4 - r) \\
-\frac{dy_i}{d\zeta} &= \frac{d}{d\zeta}\left(\frac{\partial\theta_b}{\partial x_i}\right), \quad i = (5 - r), \ldots, (8 - 2r)
\end{aligned}\right. \qquad (52)
$$

and then to $(5 - r)(4 - r)$ first-order, ordinary non-linear differential equations for

$$
\left.\begin{aligned}
\frac{dA_{ij}}{d\zeta} &= \frac{d}{d\zeta}\left(\frac{\partial^2\theta_f}{\partial x_i \partial x_j}\right) \\
\frac{dB_{ij}}{d\zeta} &= \frac{d}{d\zeta}\left(\frac{\partial^2\Theta_b}{\partial x_i \partial x_j}\right).
\end{aligned}\right\} \qquad (53)
$$

The second sets of equations in Eqs. 52 and 53 are necessary because of the dependence of θ_e on θ_b. All initial conditions, at $\zeta = 0$, for Eqs. 52 and 53 can be derived from Eqs. 26 and 30

$$
y_i(0) = (y_o)_i \,, \; A_{ij}(0) = (A_o)_{ij} \,, \; B_{ij}(0) = (B_o)_{ij} \,. \qquad (54)
$$

In summary, one needs to integrate, together with Eqs. 24 and 29, the Eqs. 52 and 53, subject to the initial conditions given by Eqs. 26, 30 and 54. The integration is carried out from $\zeta = 0$ to $\zeta = 1$ where it yields not only θ_e and $\theta_b(1)$ but also all derivatives in Eqs. 49. This system is solved for the components of $\Delta\underset{\sim}{X}$, then a new set of parameters $\underset{\sim}{X}$ is computed from Eqs. 48 and the iterative cycle repeated. The repetitions are continued until either the first $(4 - r)$ y_i's are small or one of the inequalities in Eqs. 36 is violated. Should that happen then an additional constraint is introduced, r is incremented by one, and the cycle is continued until either all limits in Eqs. 36 are reached or the remaining y_i's are sufficiently small. The result may or may not be an optimum for the initially chosen A^* or M^*. Finally, the potential optimum is tested in accordance with Eq. 47.

2. Parameter Transformation and Physical Dimension of Optimum Radiator System.

Once the optimum set $\left\{x_1,\ldots,x_4\right\}_m$ is found it is necessary to compute from this the physical dimensions L, H, t and d which define the geometry of the radiator system. To accomplish this task the set $\left\{x_1,\ldots,x_4\right\}_m$ is first transformed into the previously introduced set of normalized dimensions $\left\{L^*, H^*, t^*, d^*\right\}$. This transformation is, in general, not possible in explicit form. However, when the simplified Nusselt number relation of the form given by Eq. 35 is substituted for the more general expressions in Eqs. 8 and 9 then L^*, H^*, t^* and d^* can be expressed explicitely in terms of the parameters $\left\{x_1,\ldots,x_4\right\}$.

Define first the starred quantities.

$$N^*_{Gz} = \frac{c_p \dot{m}}{k_f L_o} \tag{55}$$

$$N^*_{Re} = \frac{4\dot{m}}{\pi\mu L_o} \tag{56}$$

$$N^*_{Nu} = c(N^*_{Re})m(N_{Pr})n \tag{57}$$

$$N^*_c = \frac{2\varepsilon\sigma T_o{}^3 L_o}{k} \tag{58}$$

which are essentially the unstarred quantities evaluated with the reference length instead of any other dimension and which are all known from system objectives and environmental conditions.

Next one needs to distinguish between laminar and turbulent coolant flow as the constants c, m, n and p are different for the two regimes.

For <u>laminar</u> flow, c = 1.86, m = n = p = 1/3

$$L^* = \frac{N^*_{Gz}}{2\pi\sqrt{c^3}} \quad \sqrt{x_1{}^3} \tag{59}$$

$$H^* = \pi\sqrt{c^3}/N^*_{Gz}\ \frac{x_2}{\sqrt{x_1}} \tag{60}$$

$$t^* = \pi^2 cN^*_c/(N^*_{Gz})^2\ \frac{x_2^{\ 2}}{x_1 x_3} \tag{61}$$

and

$$d^* = 4\pi\sqrt{c^3}\ /N^*_{Gz}\ \frac{x_2}{x_4\sqrt{x_1}} \tag{62}$$

For turbulent flow, $c = 0.023$, $m = 4/5$, $n = 1/3$, $p = 0$.

With

$$\phi_3 = \pi N^*_{Nu}/N^*_{Gz} \tag{63}$$

one obtains

$$L^* = 1/[2^5\phi_3^{\ 14}]^{1/9} x_1 \left[\frac{x_2}{x_4}\right]^{4/9} \tag{64}$$

$$H^* = 1/2[2^5\phi_3^{\ 14}]^{1/9}\ (x_2^{\ 5}x_4^{\ 4})^{1/9} \tag{65}$$

$$t^* = N^*_c/4{\cdot}[2^5\phi_3^{\ 14}]^{2/9}\ \frac{(x_2^{\ 5}x_4^{\ 4})^{2/9}}{x_3} \tag{66}$$

$$d^* = \left[2\phi_3\ \frac{x_2}{x_4}\right]^{5/9} \tag{67}$$

Finally, multiplication of the starred quantities L^*, H^*, t^* and d^* by the reference length L_o gives the dimension L, H, t and d of the fin radiator system with optimum performance.

D. Results

The ultimate presentation of the results from the radiator system optimization is the plot of the optimum non-dimensional geometric parameters L*, H*, t*, and d* versus the non-dimensional enthalpy rejection $(1 - \Theta_e)$. These graphs would include three or more parameters, namely the sink temperature Θ_s and the parameters occurring in the constraint equations. However, the optimum geometry is not expected to depend strongly on all parameters because of physical considerations, and convenient graphical presentation should be possible.

As indicated in the Introduction, the systematic optimization based on analytical extrema search techniques was developed in addition to the original program objectives but could not be completed within the contract period. The graphical presentation of the optimum geometry in terms of intended enthalpy rejection is therefore not included in this report.

However, computer codes were written on the basis of the solution discussed in Section C. These codes produce the optimum radiator parameters L*, H*, t* and d* based on the Nusselt number relationship in Eq. 35, for any particular set of input parameters computed from mission requirements and environmental conditions. These results are described in detail in Chapter IV, Sections C. 4 and D. 4.

IV. COMPUTER CODES

A. Introduction

Three separate FØRTRAN codes were developed, one for the simplified radiator system simulation, one for the minimum area optimization and one for the minimum mass system optimization.

The three codes have several subprograms in common and could be united into a single code to avoid duplication. The simulation program, however, is more efficient as a single program and will remain a tool by itself. The optimization programs, on the other hand, are means to develop a tool, namely suitable working charts from which to read optimum system parameters. Once these diagrams are obtained, the codes are no longer needed.

The three FØRTRAN codes are discussed separately in the following three sections but reference is made in the description of subprograms which have previously been discussed.

B. Radiator System Simulation

1. Objective

The purpose of the Simplified Radiator System Simulation (SRSS) is to evaluate the analysis developed in Chapter II for determining the coolant exit temperature

$$\Theta_e(U,V,\tilde{N}_c,\lambda;\Theta_s)$$

in terms of the five governing groups U, V, $\tilde{N}_c$, λ and Θ_s defined by Eqs. 13, 19 through 22.

The coolant exit temperature and also the fin base temperature are obtained by integrating simultaneously Eqs. 24 and 29, subject to the initial conditions given by Eqs. 27 and 30. The integration is performed by the Runge Kutta integration procedure described in Reference [1], under variable step size mode.

The individual program units are discussed in the subsequent sections to the extent deemed necessary for the proper utilization of the code. Following the program description are presented the input and output specifications.

2. Deck Assembly

The Simplified Radiator System Simulation (SRSS) code consists of:

one		main program	MAIN
three	SUBRØUTINE	subprograms	RKS SDRV SCNTL
three	FUNCTIØN	subprograms	ETA PØLY

A block diagram is shown in Figure 7 below.

a. The MAIN Program accepts data input and lists the accepted input data. Following the input data management, the initial conditions for integration are set, an initial step size is computed and control variables are set to control the integration procedure. Then the Runge Kutta procedure RKS is called which performs the integration and indirectly the listing of results. After return from the integration, control is transferred to the start of the program for arbitrarily many repetitions of the program execution. When all input data are exhausted then control is transferred to a normal exit.

The input data preparation is discussed in Section 3 below.

The initial conditions are given through Eqs. 27 and 30. The dependent variables Θ_f and Θ_b are, during integration, placed in the array Y; Y(1) = Θ_f and Y(2) = Θ_b. Equation 27 leads to the statement Y(1) = 1.0 and Eq. 30 is solved for Θ_b by the Newton-Raphson iteration which follows the listing of accepted input data. The iteration process leads to the statement Y(2) = THETAB (= Θ_b).

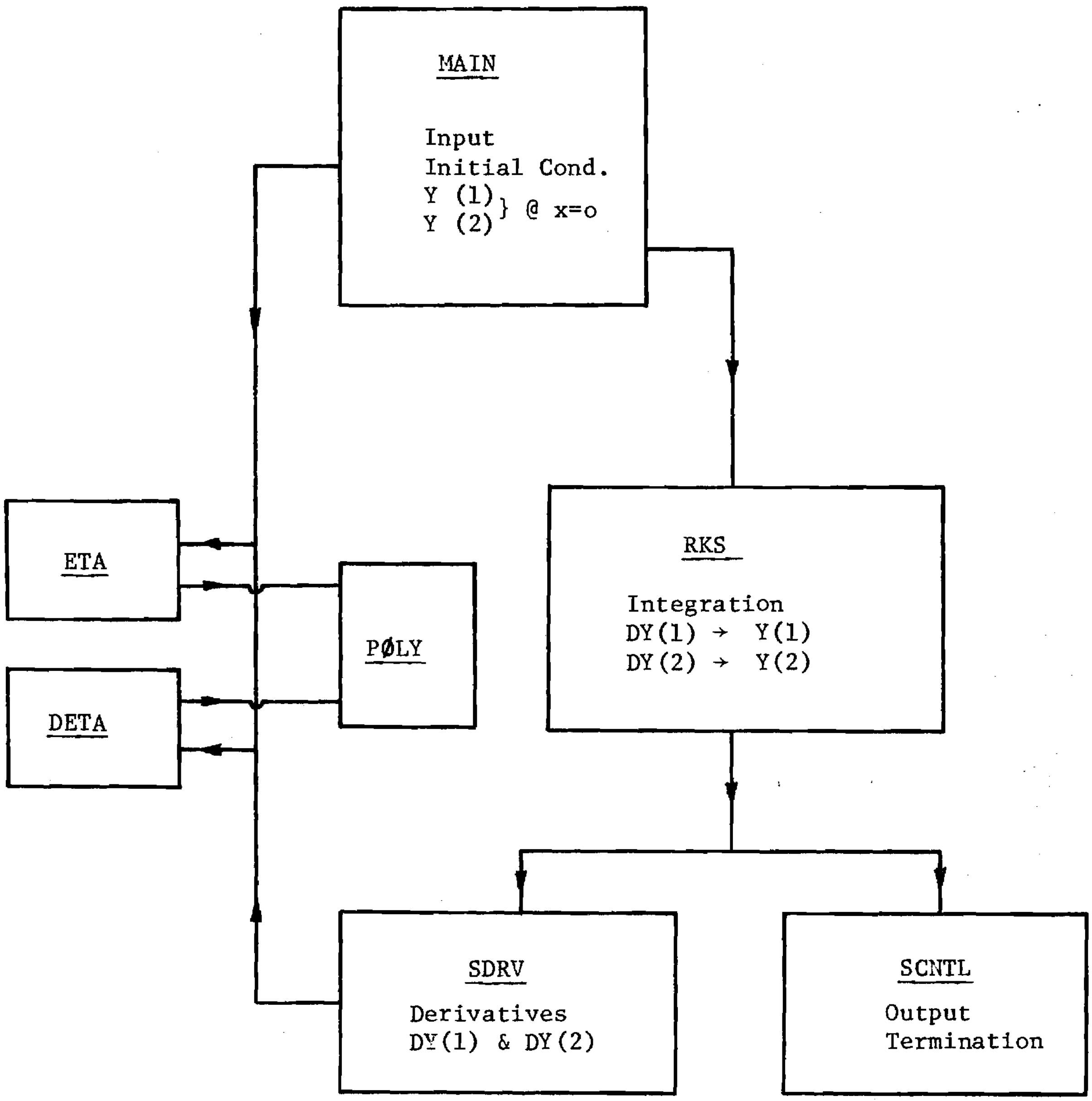

Figure 10. Block Diagram For Simplified Radiator System Simulation Code

Control variables which direct the Runge Kutta Integration RKS are:

ZZZ = 0.0	initial value for independent variable
DX = $1/(U(1 - \Theta_b))$	initial step size
IFVD = 0	variable step size selection
N = 2	two equations to be integrated
IBKP = 1	cut interval as required
NTRY = 1	normal integration mode
IERR = 0	normal error condition (DX $\neq$ 0)
A(I) = 5×10^{-5}; I = 1,2	absolute error per step
R(I) = 5×10^{-5}	relative error per step

Control variables which direct output during the integration are:

DLMT = DXWRT/500	error limit for output interval
XWRT = 0.0	first value of independent variable at first output listing
LSTEP = 0	controls change to fixed step, LSTEP = 1 once integration step exceeds write interval DXWRT
LCNT = 0	senses cut-back (LCNT = 1) of step size prior to listing of results; used to save uncut time step
ICNT = 0	integration step counter

The CALL statement for the Runge-Kutta SUB-RØUTINE is explained in Reference [1] together with the specification of necessary DIMENSIØN and EXTERNAL declarations. SDRV and SCNTL must be declared EXTERNAL. The necessary array allocations can be read from the listing of the RKS code: all arrays with variable dimension (N) must be declared in MAIN for N = 2 elements. Only the elements of Y, A and R must be specified prior to the CALL RKS statement.

b. The Runge-Kutta SUBRØUTINE RKS is described in detail in Reference [1]. The user is not expected to alter this code in any way and needs to know only the control features discussed in paragraph a above and the fact that RKS calls two subroutines SDRV and SCNTL.

c. The SUBRØUTINE SDRV serves to evaluate the derivatives $d\Theta_f/d\zeta$ = dY(1) and $d\Theta_b/d\zeta$ = dY(2) in accordance to Eqs. 24 and 29. The fin effectiveness η (N_c) and its derivative $d\eta/dN_c$ are evaluated externally by the FUNCTIØN subprograms ETA and DETA.

SDRV is called from RKS and supplies the derivatives, via argument list, as functions of the independent variable $\underset{\sim}{X}$ and dependent variables Y(1) and Y(2), to the integrating procedure RKS. SDRV is called four times per integration step.

d. The SUBRØUTINE SCNTL serves to provide

(i) output listing at prescribed intervals DXWRT,
(ii) transfer to fixed-step integration mode once the automatically selected (by RKS) step size DX exceeds the print-out interval DXWRT,
(iii) termination of the integration procedure and RETURN to the MAIN program (via RKS). The same program, with different WRITE commands is used in the Minimum Area and Minimum Mass Optimization codes.

In the argument list are available

(i) the dependent variables Y(1) and Y(2)
(ii) their derivatives DY(1) and DY(2)
(iii) the dependent variable X
(iv) the step size DX which may be altered for repeat of last step
(v) NTRY = 1 normal continuation of RKS
2 return from RKS to MAIN

3 repeat with new DX
4 restart
(vi) IFVD = 0 variable integration step
1 fixed integration step

e. <u>The FUNCTION ETA Subprogram</u> computes the fin effectiveness $\eta(N_c)$ for the unobstructed fin in accordance to Eqs. 32a and b. The power polynomial is evaluated by calling the FUNCTIØN PØLY subprogram [1].

FUNCTIØN ETA (X) receives the independent variable $X = N_c$ and returns the fin effectiveness ETA. The two functions represented by Eqs. 32 a and b apply strictly to zero sink temperature, but the effectiveness is insensitive to the sink temperature and the equations hold sufficiently well for $\Theta_s < 0.8\ \Theta_b$.

ETA (X) is called from MAIN and SDRV.

f. <u>The FUNCTIØN DETA Subprogram</u> computes the derivative $d\eta/dN_c$ of the fin effectiveness $\eta(N_c)$ for the unobstructed fin. The derivative is derived from Eqs. 32 a and b, and evaluated by calling the FUNCTIØN PØLY subprogram [1].

FUNCTIØN DETA (X) receives the independent variable $X = N_c$ and returns DETA = $d\eta/dN_c$. DETA (X) is called from MAIN and SDRV.

g. <u>The FUNCTIØN PØLY Subprogram</u> [1] serves to evaluate power polynomials f(x) of any degree (N - 1).

$$f(x) = \sum_{i=1}^{N} A_i X^i$$

by computing the recurrence expression

$$f_i = A_N$$

$$f_{k+1} = f_k X + A_{N-k}, k = 1, \ldots (N-1)$$

(N-1) times. The argument list of FUNCTIØN PØLY (N, A, X) transfers to the subprogram the number N of coefficients A_i, the one-dimensional array A(N) and the independent variable X; it returns PØLY = f(x). PØLY is called from ETA and DETA.

3. Input Data Preparation

The non-dimensional groups

$$\text{THETAS} = \Theta_s = T_s/T_o \qquad (19)$$

$$U = \pi N_{Nu}/N_{Gz} \qquad (22)$$

$$V = (i/\pi)(t/H)(k/k_f)(\bar{N}_c/N_{Nu}) \qquad (21)$$

$$\text{FNCBR} = \bar{N}_c = 2\varepsilon\sigma T_o^3 H^2/(kt) \qquad (20)$$

$$\text{RH}\emptyset\text{D} = \lambda = 4H/d \qquad (13)$$

DXWRT = $\Delta z/L$, output intervals

are computed and punched, in the above sequence, on two cards in

FØRMAT (5F16.8)

There may be arbitrarily many pairs of cards as specified above, one pair for each desired simulation. They will be executed in succession. The End-of-Job card will cause normal exit from the program.

The expected run time on the UNIVAC 1108 is 0.24 seconds per simulation plus necessary compiling and collecting times. There were 32 runs executed in 14.8 seconds.

4. Output Presentation

For each simulation are printed, on a separate page, first the governing parameters as read in:

THETAS = Θ_s	,	defined by	Eqs. 4 & 19
U	,	"	Eq. 22
V	,	"	Eq. 21
FNCBAR = $\bar{N}_c$	,	"	Eq. 20
LAMBDA = λ	,	"	Eq. 13

and then a table consisting of seven columns. In the first two columns are listed, as functions of axial distance ZETA = ζ at the selected intervals

$\Delta\zeta$ = DXWRT, the coolant fluid temperature THETAF = θ_f and the fin base temperature THETAB = θ_b. The positions ZETA = ζ are listed in the sixth column.

The conduction parameter NC = N_c, the combined fin-plus-tube effectiveness ETABAR = $\bar{\eta}$, defined by Eq. 11, and the fin effectiveness (unobstructed fin, Eqs. 32 a and b) ETA = $\bar{\eta}$, are listed, respectively, in the third, fourth and fifth columns. The last columns indicate the integration steps required to reach the respective axial position ζ. The desired coolant fluid exit temperature θ_e $(U,V,\bar{N}_c,\lambda;\Theta_s)$ is found in the last entry of the first column.

Figure 11 shows a typical output listing

C. Minimum Area Optimization

1. Objective

The Minimum Area Optimization (MAO) code serves to find the minimum coolant fluid exit temperature for a given projected fin panel area, on the basis of the optimization analysis developed in Chapter III and the constraints as discussed in Section III-2. From the results, evaluated for a number of selected areas, one can determine the minimum area required for a chosen heat rejection rate. The optimum parameter set $\underset{\sim}{X}$ is sought which satisfies Eqs. 33, 36, 40 and 41 by performing the iterations specified in Eqs. 48 through 53 until Eq. 33 is satisfied.

From the optimum parameter set $\underset{\sim}{X}$ one computes the normalized system dimensions L*, H*, t* and d* in accordance to Eqs. 59 through 62 or Eqs. 64 through 67, depending on the flow regime in the coolant channels.

The necessary derivatives occurring in Eqs. 50 and 51 are obtained by Runge-Kutta Integration of the first-order, ordinary, non-linear differential equations given by Eqs. 52 and 53.

The individual program units are discussed in the following sections. Reference is made to program description in Section 3 of this Chapter and to Reference [1].

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02

THETA-S =	.200000
U =	.100000+01
V =	.100000+01
FNCBAR =	.200000+00
LAMBDA =	.250000+02

THETAF	THETAB	NC	ETABAR	ETA	ZETA	STEP NO
1.000000	.724992	.076213	1.001229	.919403	.00	1
.973292	.713938	.072780	1.004461	.922709	.10	2
.948092	.703261	.069563	1.007515	.925832	.20	4
.924291	.692944	.066546	1.010401	.928785	.30	5
.901791	.682975	.063715	1.013130	.931576	.40	6
.880499	.673338	.061056	1.015711	.934216	.50	7
.860331	.664019	.058556	1.018154	.936714	.60	8
.841212	.655007	.056204	1.020465	.939079	.70	9
.823068	.646288	.053989	1.022655	.941319	.80	10
.805835	.637851	.051902	1.024729	.943441	.90	11
.789452	.629684	.049934	1.026696	.945453	1.00	12

FIGURE 11. SAMPLE RESULTS OF SIMPLIFIED RADIATOR SYSTEM SIMULATION

2. Deck Assembly

In its current state the Minimum Area Optimization (MAO) code consists of

1		main program	MAIN	
14	SUBRØUTINE	subprograms	RKS SDRV SCNTL	integration
			BNDCND RESBND REST	restraints
			NDERV MDER NCDERV MIXDER DERV	partial derivatives
			INITIAL INTMIX	initial conditions
			FMINV	matrix inversion
5	FUNCTIØN	subprograms	ETA DETA DDETA DDDETA PØLY	η and its derivatives

The basic concept of the program is as described in Chapter B before and the block diagram in Figure 7 applies in principle. The exceptions are

(i) there are 20 simultaneous differential equations to be solved:

2 for Θ_f and Θ_b

6 for the derivatives of Θ_f and Θ_b with respect to U, V and $\bar{N}_c$

12 for the second derivatives of Θ_f and Θ_b with respect to U, V, and $\bar{N}_c$,

(ii) the initial conditions on the last 18 differential equations are obtained in subroutines,

(iii) partial derivatives occurring in the differential equations for the last 18 of the above derivatives are computed by subroutines,

(iv) at the end of each integration, the system of Eq. 49 is solved by FMINV and the integration repeated until the optimum is reached.

a. The MAIN Program performs the same functions as described in Chapter IV, Section B.2.a. and, in addition, calls INITIAL and INTMIX which compute the remaining 18 initial conditions for the partial derivatives as defined through Eq. 54. Moreover, instead of returning to the next input data set after completion of an integration, new system parameters $\underset{\sim}{X}$ are computed by solving, via FMINV, the system of Eq. 49. The results are tested, through SUBRØUTINE BNDCND, to satisfy the Inequalities 36. If necessary, the newly computed parameters are adjusted to fall within the above limits, and the integration is repeated.

b. The SUBRØUTINES RKS, SDRV and SCNTL perform the integration as explained in Sections B.2.b, c and d. There are, however, 18 additional dependent variables Y(3), ..., Y(20) to be integrated by RKS and, consequently, 18 additional derivatives to be evaluated in accordance with Eqs. 52 and 53. These derivatives are evaluated by calling DERV for $\partial\Theta_f/\partial X_i$, $\partial\Theta_b/\partial X_i$, $\partial^2\Theta_f/\partial X_i^2$ and $\partial^2\Theta_b/\partial X_i^2$ and by calling MIXDER for $\partial^2\Theta_f/\partial X_i\partial X_j$ and $\partial^2\Theta_b/\partial X_i\partial X_j$, $i \neq j$. SCNTL contains a slightly altered output specification.

c. The Restraint SUBROUTINES BNDCND, RESBND and REST serve to, respectively,

(i) test newly computed components $\underset{\sim}{X}$ for compliance with Inequalities 36.

(ii) solve Eqs. 40 and 41 for x_3 and x_4.

When newly computed components $\underset{\sim}{X}$ do not comply with Inequalities 36 then they are set to meet the minimum and maximum conditions and the system of Eq. 49 is solved again, all from within BNDCND.

SUBRØUTINE REST is the only particular program which differentiates the two optimization modes, minimum area and minimum mass. It may be replaced to accommodate other constraints. BNDCND and REST are called from MAIN.

d. The SUBRØUTINES NDERV, MDER, NCDER, MIXDER and DERV are used to compute, respectively,

(i) N and its derivatives $dN/d\lambda$, $d^2N/d\lambda^2$ from Eq. 17,

(ii) M and its derivatives, up to third order, with respect to its arguments λ and N_c, in accordance to Eqs. 12, 15 and 16,

(iii) N_c and its derivatives $\partial N_c/\partial\Theta_b$, $\partial^2 N_c/\partial\Theta_b{}^2$ and $\partial^2 N_c/\partial T \partial \bar{N}_c$,

(iv) the mixed derivatives defined by Eq. 53 for $i \neq j$,

(v) the derivatives defined by Eqs. 52 and 53.

e. The SUBRØUTINES INITIAL and INTMIX serve to compute the initial conditions for the dependent variable Y(3), ..., Y(20), at the channel inlet $\zeta = 0$ which represent simple and mixed derivatives $\partial^2\Theta_f/\partial X_i \partial X_j$ and $\partial^2\Theta_b/\partial X_i \partial X_j$ in Eq. 53.

f. The SUBRØUTINE FMINV is capable of performing two related tasks:

(i) to invert a square, invertible matrix $\underset{\approx}{A}$

(ii) to solve a non-trivial system of equations $\underset{\approx}{A}\underset{\sim}{Z} = \underset{\sim}{X}$.

The solutions are obtained through a sequence of elementary row operations which lead from the properly augmented coefficient matrix to the row-reduced echelon matrix, a standard procedure described in most elementary introductions to linear algebra [1].

SUBROUTINE FMINV (A, X, N, M) accepts, through its argument list, the square, invertible matrix $\underset{\approx}{A}$ of rank N, and if task (i) above is intended, M is set equal to M = 2N. Then, upon return from FMINV there will be the inverted matrix $\underset{\approx}{A}^{-1}$ placed in XMAT(I,J) with I = 1, ..., N, J = N + 1, N + 2, ..., 2N. The two-dimensional array XMAT is transferred to the calling program via a CØMMØN declaration. When task (ii) above is intended, M is set equal to M = N + 1 and, upon return from FMINV, the unknown vector $\underset{\sim}{Z}$ is placed in the one-dimensional array $\underset{\sim}{X}$.

FMINV is used to solve Eq. 49 and is called from MAIN and from BNDCND.

g. <u>The FUNCTIØN subprograms ETA, DETA and PØLY</u> are described in Sections B.2.e, f, and g of this chapter.

h. <u>The FUNCTIØN subprograms DDETA and DDDETA</u> are used to compute the second and third-order derivatives $d^2\eta/dN_c^{\ 2}$ and $d^3\eta/dN_c^{\ 3}$ as derived from Eqs. 32 a and b. The derivatives are evaluated via FUNCTIØN PØLY subprogram.

3. Input Data Preparation

Each optimization run is carried out for a selected ASTAR = A^* (Eq. 38) and TSTAR = t^* (Eq. 41) as the independent variables. The necessity of specifying t^* is not yet completely established at this time but included in the program for additional flexibility and to prevent the search from reading excessively large values of t^*.

The optimization produces

(i) the optimum coolant exit temperature

(ii) the optimum parameters $\underset{\sim}{X} = \{x_1, \ldots, x_4\}$ from which to compute L^*, H^*, d^* and λ (Eqs. 59-67).

For each optimization one computes

THETAS = Θ_s	, defined by	Eqs. 19 & 4
U, starting value	, "	"	Eq. 22
V, starting value	, "	"	Eq. 21
FNCBR = $\bar{N}_c$ starting value	, "	"	Eq. 20
ASTAR = A*	, "	"	Eq. 40

and selects

DXWRT = $\Delta\zeta$ the axial interval for which results are to be printed.

The first five values are punched on one card in

FØRMAT (5F16.8).

The last value is punched on a second card in

FORMAT(F16.8)

There may be arbitrarily many pairs of cards as specified above, one pair for each optimization run. They will be carried out in succession. The End-of-Job card will cause normal exit from the program.

The expected run time per optimization is approximately 15 seconds plus necessary compilation and collection times.

4. Presentation of Results

Each iteration produces one page of output, first the three parameters THETAS, ASTAR and TSTARI as read in. Next the current values of the system parameters U, V, FNCBAR = $\bar{N}_c$, LAMBDA = λ and the identification of the flow regime, followed by the iteration count for establishing initial conditions

The table lists, as functions of ζ = Z/L, in this order

THETAF = $\theta_f(\zeta)$ coolant temperature

THETAB = $\theta_b\ (\zeta)$ fin base temperature

NC = $N_c(\zeta) = \bar{N}_c\theta_b{}^3$, Eq. 14

ETABAR = $\bar{\eta}$, defined by Eq. 11

ETA = η, defined by Eq. 32

M defined by Eq. 12

N defined by Eq. 17

X = ζ, the non-dimensional distance along the channel.

Following the table is a list of the three system parameters U, V, $\bar{N}_c$ and the first and second derivatives of Θ_f with respect to these parameters. Finally are listed the newly computed changes of the above parameters.

A typical listing of the results is shown in Figure 9.

```
THETA-S =      .70300000
  ASTAR =      .675000

      U =    250.000000
      V =      .000050
  ENCBR =      .000100
 LAMBDA =      .037736
```

NUMBER OF ITERATIONS = 14

THETAF	THETAR	NC	ETABAR	ETA	M	N	ZETA
1.0000000	.9979813	.0000094	53.0999905	.9998844	.1801294	53.8198819	.0000000
.92[illegible]1307	.9188655	.0000776	53.0999919	.9999098	.1801264	53.8198819	.2000000
.8677819	.8669164	.0000652	53.0999928	.9999242	.1801247	53.8198819	.4000000
.8309971	.8303729	.0000573	53.0999933	.9999334	.1801236	53.8198819	.6000000
.8039970	.8035309	.0000519	53.0999938	.9999397	.1801229	53.8198819	.8000000
.7835871	.7832305	.0000480	53.0999938	.9999441	.1801224	53.8198819	1.0000000

PARAMETERS AT END OF TUBE

```
                               THETAF =  .783587

       U =  .250000+03              V =  .500000-04         NCBAR =  .100000-03
   DTFDU = -.247174-05          DTFDV =  .117912+00       DTFNCBAR =  .771548-04
 D2TFD2U =  .197315-07        D2TFD2V =  .979100+01     D2TFD2NCBAR =  .844942-03
D2TFDUDV =  .530919-05   D2TFDUDNCBAR =  .105256-05    D2TFDVDNCBAR =  .525590+01

 DELTA U =  .126478+03        DELTA V = -.363925-04     DELTA NCBAR = -.224943-01
```

OPTIMUM REACHED

FIGURE 12. RESULTS LISTING OF MINIMUM AREA OPTIMIZATION

D. Minimum Mass Optimization

1. Objective

The objective of the Minimum Mass Optimization (MMO) code is identical to that discussed in Section C above, except that the constraints are replaced by the constraints developed in Section III-3 of this report; the minimum mass is thought. Equation 46 replaces Eqs. 40 and 41.

2. Deck Assembly

The MMO code is assembled identically to the MAO code described in Section C.2 above except the SUBRØUTINE REST is replaced by the SUBRØUTINE CØNST which serves to compute $x_4 = \lambda$ from Eq. 46, together with all the necessary derivatives of λ with respect to $x_1 = U$, $x_2 = V$ and $x_3 = \bar{N}_c$. CØNST is called from MAIN. RESBND is not required.

3. Input Data Preparation

Each optimization is carried out for a selected M^*_{tot} as the independent variable and for the two parameters N^*_{Nu} and ϕ_2, defined by Eqs. 46, 42 and 57, respectively. The optimization produces

(u) the optimum (minimum) coolant exit temperature

(ii) the optimum system parameters $\underset{\sim}{X}$ from which to compute $\{L^*, H^*, t^*, d^*\}$ through Eqs. 59-67.

For each optimization are computed

THETAS = Θ_s	defined by Eqs.	4 & 19
U } starting values		22
V }		21
FNCBAR = $\bar{N}_c$		20
TØTMAS = M^*_{tot} , selected		46
PHI2 = ϕ_2		44

$$\text{ALPHA} = \alpha = N^*_{Nu}\sqrt{c}\ \sqrt[3]{2\pi/N^*_{Gz}}$$

and selected

DXWRT = $\Delta\zeta$ the axial interval for which results are to be printed.

DA, DR absolute and relative integration step errors.

The data values are punched on the data card in NAMELIST format. The NAMELIST is called INPUT.

There may be arbitrarily many additional input data cards as specified above, or with only one datum, one NAMELIST for each optimization run. They will be carried out in succession until an End-of-Job card causes normal exit from the program.

The expected run time per optimization is approximately 20 seconds plus necessary machine preparation times.

4. Representation of Results

Results are presented in the format identical to that described in section C.4 above, except that instead of the single TSTAR1 are listed MSTAR = M*, PHI2 = ϕ_2 and FNUSTR = N^*_{Nu}, as read in. The representative output example is shown in Figure 10.

```
THETA-S =       .60000000
      U =       13.363489
      V =        2.792685
  FNCBR =        5.731686
 TOTMAS =       95.000000
   PHI2 =     2000.000000
  ALPHA =        5.000000
 LAMBDA = 31297273.250000
```

NUMBER OF ITERATIONS = 8

THETAF	THETAB	NC	ETABAR	ETA	M	N	X
1.0000000	.7686288	2.6027493	.3775592	.3775592	1.0000000	.0000001	.0000000
.7134382	.6486320	1.0316816	.5284999	.5284998	1.0000000	.0000001	.2000000
.6322974	.6138584	1.1674339	.5047780	.5047780	1.0000000	.0000001	.4000000
.6088749	.6038113	1.2169663	.4969006	.4969006	1.0000000	.0000001	.6000000
.6024210	.6010400	1.2322024	.4945601	.4945600	1.0000000	.0000001	.8000000
.6006592	.6002832	1.2364472	.4939149	.4939148	1.0000000	.0000001	1.0000000

PARAMETERS AT END OF TUBE

```
                                          THETAF =   .600659

                     U =   .133635+02          V =   .279269+01            NCBAR =   .573169+01
                 DTFDU =  -.496030-04      DTFDV =  -.131301-03          DTFNCBAR =  -.384840-04
               D2TFD2U =   .105462-03    D2TFD2V =   .455954+04       D2TFD2NCBAR =   .120270+03
               D2TFDUDV = -.229946-02  D2TFDUDNCBAR =  .294970-03     D2TFDVDNCBAR =  -.740525+03

INCR. SOUGHT   DELTA U =   .100314+00    DELTA V =  -.807482-01      DELTA NCBAR =  -.497181+00

INCR. USED     DELTA U =   .100314+00    DELTA V =  -.832025-01      DELTA NCBAR =  -.497181+00
```

INSIGNIFICANT IMPROVEMENT OVER LAST STEP

FIGURE 13. RESULTS LISTING OF MINIMUM MASS OPTIMIZATION

V. CONCLUSIONS

The work presented herein resulted in a simplified radiator system analysis and a systematic optimization procedure.

Comparison of the simplified with the rigorous [1] system analyses indicated that the agreement between the two analyses can be expected to be within approximately 5%.

The optimization procedures carried out lead frequently to an optimum on the boundaries of the parameter domain. Mass optimization tends toward widley spaced tubes between thin fins.

Optimization was originally intended to be achieved through the parametric study of trends rather than through analytical procedures. Within the resources provided by this contract two analytical iterative optimization procedures were developed beyond the original goal of work. These procedures lead to the maximum heat rejection for given system area or system mass. Future work should be aimed toward the development of

(1) a parameter domain within which relative extrema exist,

(2) suitable working diagrams, through repeated applications of the developed codes, which depict the optimum geometric system parameters and produce either the least area or the least weight requirements for a given heat rejection rate.

BIBLIOGRAPHY

1. Black, W. Z. and Wulff, W., "Study of Design Parameters of Space Base and Space Shuttle Heat Rejection Systems," Final Report, Contract No. NAS 9-10415, Georgia Institute of Technology, Atlanta; April 1972.

2. Black, W. Z. and Wulff, W., "Study of Design Parameters of Space Base and Space Shuttle Heat Rejection Systems," Initial Phases I, II and III, Contract No. NAS 9-10415, Georgia Institute of Technology, Atlanta; February 1971.

3. Hausen, H., VDI Beihefte, Verfahrenstechnik, 1943, p. 91.

4. Seban, R. A. and Shimazaki, T. T.,"Heat Transfer to a Fluid Flowing Turbulently in a Smooth Pipe with Walls at Constant Temperature," Trans. ASME, Vol. 73, p. 803, 1951.

5. Lieblein, S., "Analysis of Temperature Distribution and Radiant Heat Transfer Along a Rectangular Fin." NASA TN D-196, 1959.

6. Bartas, J. G. and Sellers, W. H., "Radiation Fin Effectiveness," J. Heat Transfer, C82, 73-75, 1960.

7. Sparrow, E. M. and Cess, R. D., Radiation Heat Transfer, Brooks/Cole Publishing Company, p. 173, Fig. 6-9, 1966.

8. dto, p. 175, Fig. 6-11.

APPENDIX A

COMPUTER CODE FOR SIMPLIFIED RADIATOR SYSTEM SIMULATION

```
@FOR,IS MAIN
FOR S9A-07/25/72-22:59:39 (,0)

   MAIN PROGRAM

   STORAGE USED: CODE(1) 000464; DATA(0) 000355; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003   SDR     000014
    0004   MCT     000006

   EXTERNAL REFERENCES (BLOCK, NAME)

    0005   SDRV
    0006   SCNTL
    0007   ETA
    0010   DETA
    0011   RKS
    0012   NINTR$
    0013   NWDU$
    0014   NI02$
    0015   NRDU$
    0016   SQRT
    0017   ASIN
    0020   NSTOP$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001    000150 100L      0001    000327 105L      0001    000345 110L      0000    000265 120F      0001    000405 232G
    0001    000007 45L       0000    000233 5F        0000    000234 50F       0000    000236 55F       0001    000131 85L
    0001    000145 90L       0000    000304 900F      0000    000311 905F      0001    000452 920L      0000    000313 925F
    0001    000147 95L       0001    000460 950L      0000 R  000030 A         0000 R  000213 AYY       0000 R  000205 Ai
    0000 R  000214 BYY       0010 R  000000 DETA      0000 R  000220 DETZ      0003 R  000007 DFM       0003    000010 DFMX
    0003 R  000011 DFNX      0004 R  000000 DLMT      0000 R  000060 DLY       0003    000012 DROU      0003    000013 DROV
    0000 R  000224 DX        0004 R  000003 DXWRT     0000 R  000014 DY        0000 R  000140 DYST      0000 R  000221 DYY
    0007 R  000000 ETA       0000 R  000216 ETY       0000 R  000215 ETYY      0003 R  000006 FM        0003 R  000005 FN
    0000 R  000212 FNC       0003 R  000002 FNCBR     0000 I  000232 I         0000 I  000227 IBKP      0004 I  000001 ICNT
    0000 I  000231 IERR      0000 I  000225 IFVD      0004 I  000005 LCNT      0004 I  000004 LSTEP     0000 I  000226 N
    0000 I  000207 NCT       0000 I  000230 NTRY      0000 R  000074 PD        0000 R  000044 R         0003 R  000004 RHOD
    0006 R  000000 SCNTL     0000 R  000110 SD        0005 R  000000 SDRV      0000 R  000206 THETAB    0000 R  000204 THETAS
    0003 R  000003 TH4       0000 R  000210 T2        0000 R  000211 T3        0003 R  000000 U         0003 R  000001 V
    0004 R  000002 XWRT      0000 R  000000 Y         0000 R  000124 YS        0000 R  000170 YSIMP     0000 R  000154 YST
    0000 R  000217 YY        0000 R  000222 ZZ        0000 R  000223 ZZZ
```

```
 00100        1*      C
 00100        2*      C      SIMPLIFIED RADIATOR SYSTEM SIMULATION
 00100        3*      C      *************************************
 00100        4*      C
 00100        5*      C          THETAS,U,V,FNCBR, AND RHOD ARE SYSTEM PARAMETERS
 00100        6*      C          DXWRT IS THE INCREMENT OF AXIAL DISTANCE FOR OUTPUT LISTING
```

```
00100   C                FORMAT (5F16.8)
00100   C
00101             EXTERNAL SDRV,SCNTL
00103             DIMENSION Y(12),DY(12),A(12),R(12),DLY(12),PD(12),SD(12),YS(12),
00103            1         DYST(12),YST(12),YSIMP(12)
00104             COMMON /SDR/ U,V,FNCBR,TH4,RHOD,FN,FM,DFM,DFMX,DFNX,DROU,DROV/MCT/
00104            1            DLMT,ICNT,XWRT,DXWRT,LSTEP,LCNT
00104   C
00104   C
00105             FNN(X)   = (X+3.570796-SQRT(X*(X+2.0))-ASIN(1.0/(1.0+X)))/X
00106             FFS(X)   = (SQRT(X*(X+2.0))+ASIN(1.0/(X+1.0))-1.570796)/X
00107             FFN(X,Y)= 1.0-Y*(0.1460*Y-0.02866)/X
00110             DFFN(X,Y)=(-0.2920*Y+0.02866)/X
00111             DFFNX(X,Y)= Y*(0.1460*Y-0.02866)/(X*X)
00112             DFFS(X)  = -SQRT((X+2.0)/X)/(X*(X+1.))+(1.5708-ASIN(1.0/(X+1.0)))/
00112            1         (X*X)
00112   C
00113
00113             WRITE(6,5)
00115           5 FORMAT(1H1)
00115   C
00116          45 READ(5,50,END=950) THETAS,U,V,FNCBR,RHOD,DXWRT
00126          50 FORMAT(5F16.8)
00127             WRITE(6,55) THETAS,U,V,FNCBR,RHOD
00136          55 FORMAT(1H0,10X,10HTHETA-S = ,F19.6,/,
00136            1         11X,10H      U = ,E20.6,/,
00136            2         11X,10H      V = ,E20.6,/,
00136            3         11X,10H FNCBAR = ,E20.6,/,
00136            4         11X,10H LAMBDA = ,E20.6,///)
00136   C
00137             IF(THETAS.GE. 1.0) GO TO 920
00141             FN       = FNN(RHOD)
00142             DFNX     = (-FN+1.0-SQRT(RHOD*(RHOD+2.0)))/RHOD
00143             TH4      = THETAS**4
00144             IF(V.GT.0.2) GO TO 90
00146             A1       = 2.0+1.0/(V*ETA(FNCBR))
00147             IF(A1.GE.2.45) GO TO 85
00151             THETAB   = 1.0-1.0/(2.0*A1)
00152             GO TO 95
00153          85 THETAB   = 1.0-(A1-SQRT(A1**2-6.0))/6.0
00154             GO TO 95
00155          90 THETAB   = 0.9
00156          95 NCT      = 0
00157         100 T2       = THETAB**2
00160             T3       = T2*THETAB
00161             FNC      = FNCBR*T3
00162             FM       = FFN(RHOD,FNC)*FFS(RHOD)
00163             DFM      = DFFN(RHOD,FNC)*FFS(RHOD)
00164             AYY      = T3*THETAB-TH4
00165             BYY      = 1.0-THETAB
00166             ETYY     = ETA(FNC)
00167             ETY      = ETYY*FM+FN
00170             YY       = 1.0/V-ETY*AYY/BYY
00171             DETZ     = (DFM*ETYY+FM*DETA(FNC))*3.0*T2*FNCBR
00172             DYY      = -AYY/BYY*(DETZ+ETY/BYY)-4.0*ETY*T3/BYY
00173             ZZ       = THETAB-YY/DYY
00174             IF(NCT.GT.20) WRITE(6,900)
```

```
00177                IF(ZZ.LT.1.0) GO TO 105
00201                THETAB  = (THETAB+1.0)/2.0
00202                NCT     = NCT+1
00203                GO TO 100
00204            105 IF(ABS(ZZ-THETAB)/ZZ.LT.1.0E-06) GO TO 110
00206                NCT     = NCT+1
00207                THETAB  = ZZ
00210                GO TO 100
00210        C
00211            110 Y(1)    = 1.0
00212                Y(2)    = THETAB
00213                ZZZ     = 0.0
00214                DX      = 1.0/(U*(1.0-THETAB))
00215                IFVD    = 0
00216                IF(DX.GT.DXWRT) DX = DXWRT
00220                N       = 2
00221                IBKP    = 1
00222                NTRY    = 1
00223                IERR    = 0
00223        C
00224                DLMT    = DXWRT/500.0
00225                XWRT    = 0.0
00226                LSTEP   = 0
00227                LCNT    = 0
00230                ICNT    = 0
00231                DO 115 I=1,12
00234                A(I)    = 5.0E-05
00235            115 R(I)    = 5.0E-05
00235        C
00237                WRITE(6,120)
00241            120 FORMAT(1H0,13X,6HTHETAF,14X,6HTHETAB,16X,2HNC,17X,6HETABAR,15X,
00241              1       3HETA,,8X,4HZETA,6X,7HSTEP NO,/)
00241        C
00242                CALL RKS(SDRV,SCNTL,Y,DY,A,R,ZZZ,DX,N,IFVD,IBKP,NTRY,IERR,
00242             1          DLY,PD,SD,YS,YST,DYST,YSIMP)
00243                WRITE(6,905)
00245                GO TO 45
00246            900 FORMAT(1H0,20HNEWTON-RAPHSON FAILS)
00247            905 FORMAT(1H ,/////)
00250            920 WRITE(6,925)
00252            925 FORMAT(1H0,37HRADIATIVE HEATING CANNOT BE SIMULATED)
00253                GO TO 45
00254            950 STOP
00255                END

      END OF COMPILATION:       NO  DIAGNOSTICS.
```

```
@FOR,IS SUB1
FOR S9A-07/25/72-23:00:14 (,0)

   SUBROUTINE SORV      ENTRY POINT 000150

   STORAGE USED: CODE(1) 000155; DATA(0) 000037; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003    SDR      000014
    0004    SDC      000003

   EXTERNAL REFERENCES (BLOCK, NAME)

    0005    ETA
    0006    DETA
    0007    ASIN
    0010    SQRT
    0011    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000136 10L        0001     000103 SL         0000 R 000005 A0         0000 R 000006 A1         0000 R 000007 A2
    0000 R 000010 A3          0000 R 000011 A4          0000 R 000012 A5         0006 R 000000 DETA       0003 R 000007 DFM
    0003     000010 DFMX       0003     000011 DFNX       0003     000012 DROU       0003     000013 DROV       0005 R 000000 ETA
    0004 R 000001 ETY         0004 R 000002 ETZ         0000 R 000003 FFN        0000 R 000004 FFS        0003 R 000006 FM
    0003 R 000005 FN          0003 R 000002 FNCBR       0000     000024 INJP$      0003 R 000004 RHOD       0003 R 000003 TH4
    0003 R 000000 U           0003     000001 V          0000 R 000000 Y2         0000 R 000001 Y3         0000 R 000002 Y4
    0004 R 000000 Z


 00101       1*            SUBROUTINE SORV(Y,DY,X)
 00101       2*      C
 00101       3*      C     COMPUTES DERIVATIVES
 00101       4*      C
 00103       5*            DIMENSION Y(12),DY(12)
 00104       6*            COMMON /SDR/ U,V,FNCBR,TH4,RHOD,FN,FM,DFM,DFMX,DFNX,DROU,DROV/SDC/
 00104       7*           1              Z,ETY,ETZ
 00104       8*      C
 00105       9*            Y2        = Y(2)**2
 00106      10*            Y3        = Y(2)*Y2
 00107      11*            Y4        = Y2*Y2
 00110      12*            Z         = FNCBR*Y3
 00111      13*            ETY       = ETA(Z)
 00112      14*            FFN       = 1.-Z*(0.1460*Z-0.02866)/RHOD
 00113      15*            FFS       = (SQRT(RHOD*(RHOD+2.))+ASIN(1./(RHOD+1.))-1.5708)/RHOD
 00114      16*            FM        = FFN*FFS
 00115      17*            DFM       = (-0.2920*Z+0.02866)/RHOD*FFS
 00116      18*            ETZ       = ETY*FM+FN
 00117      19*            DY(1)     = -U*(Y(1)-Y(2))
 00120      20*            A0        = Y4-TH4
```

```
00121                 IF(A0.GT.1.0E-08) GO TO 5
00123                 DY(2)    = 0.0
00124                 GO TO 10
00125               5 A1       = Y(1)-Y(2)
00126                 A2       = (ETY*DFM+DETA(Z)*FM)
00127                 A3       = 3.*A2*Y2*FNCBR/ETZ
00130                 A4       = 4.0*Y3/A0
00131                 A5       = 1.0+A1*(A3+A4)
00132                 DY(2)    = DY(1)/A5
00132         C
00133              10 CONTINUE
00134                 RETURN
00135                 END

         END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS SUB2
FOR S9A-07/25/72-23:01:21 (,0)

   SUBROUTINE SCNTL      ENTRY POINT 000146

   STORAGE USED: CODE(1) 000173; DATA(0) 000016; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003   SDC     000003
    0004   MCT     000005

   EXTERNAL REFERENCES (BLOCK, NAME)

    0005   NWDU$
    0006   NI02$
    0007   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001    000054 5L        0001    000061 50L       0000    000002 55F       0001    000134 60L       0004 R 000000 DLMT
    0000 R  000000 DXSTR     0004 R  000003 DXWRT     0003 R  000001 ETY       0003 R  000002 ETZ       0004 I 000001 ICNT
    0000    000010 INJP$     0000 I  000001 LCNT      0004 I  000004 LSTEP     0004 R  000002 XWRT      0003 R 000000 Z


00101               SUBROUTINE SCNTL(Y,DY,DX,X,NTRY,IFVD)
00101          C
00101          C    CONTROLS INTEGRATION
00101          C
00103               DIMENSION Y(12),DY(12)
00104               COMMON /SDC/ Z,ETY,ETZ /MCT/ DLMT,ICNT,XWRT,DXWRT,LSTEP
00105               ICNT     = ICNT+1
00106               IF(DX.GE.DXWRT.AND.ICNT.GT.1) LSTEP = 1
00110               IF(ABS(X-XWRT).LT.DLMT) GO TO 50
00112               IF(XWRT.GT.X) GO TO 5
00112          C
00114               DXSTR    = DX
00115               DX       = DX+XWRT-X
00116               LCNT     = 1
00117               NTRY     = 3
00120               RETURN
00120          C
00121             5 NTRY     = 1
00122               RETURN
00122          C
00123            50 WRITE(6,55) Y(1),Y(2),Z,ETZ,ETY,X,ICNT
00134            55 FORMAT(1H ,5F20.6,F10.2,I10)
00135               IF(LCNT.EQ.1) DX = DXSTR
00137               LCNT     = 0
00140               IF(ABS(1.0-XWRT).LE.DLMT) GO TO 60
00142               XWRT     = XWRT+DXWRT
```

```
00143              NTRY    = 1
00144              IF(LSTEP.EQ.0) RETURN
00146              DX      = DXWRT
00147              IFVD    = 1
00150              RETURN
00150         C
00151           60 NTRY    = 2
00152              RETURN
00153              END

        END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS SUB3
FOR S9A-07/25/72-23:01:28 (,0)

   FUNCTION ETA          ENTRY POINT 000036

   STORAGE USED: CODE(1) 000044; DATA(0) 000022; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   POLY
    0004   EXP
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000016 1L        0000 R 000001 A          0000 R 000010 B          0000 R 000000 ETA        0000    000014 INJP$
    0003 R 000000 POLY


 00101       1*               FUNCTION ETA(X)
 00101       2*       C
 00101       3*       C       COMPUTES FIN EFFECTIVENESS ETA
 00101       4*       C
 00103       5*               DIMENSION A(7), B(2)
 00104       6*               DATA A(1),A(2),A(3),A(4),A(5),A(6),A(7)/0.10E+01, -0.1163143E+01,
 00104       7*              1     0.1478836E+01, -0.1267550E+01, 0.6325223E+00, -0.1627067E+00,
 00104       8*              2     0.1654223E-01/ B(1),B(2)/0.6866095E+00, -0.2297718E+00/
 00116       9*               IF(X.GT.2.5) GO TO 1
 00120      10*               ETA   = POLY(7,A,X)
 00121      11*               RETURN
 00122      12*             1 ETA   = B(1)*EXP(B(2)*X)
 00123      13*               RETURN
 00124      14*               END

      END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS SUB4
FOR S9A-07/25/72-23:01:35 (,0)

   FUNCTION DETA        ENTRY POINT 000036

   STORAGE USED: CODE(1) 000044; DATA(0) 000021; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   POLY
    0004   EXP
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000016 1L       0000 R 000001 A         0000 R 000007 B         0000 R 000000 DETA       0000    000013 INJP$
    0003 R 000000 POLY

 00101        1*            FUNCTION DETA(X)
 00101        2*      C
 00101        3*      C     COMPUTES FIRST DERIVATIVE     DETA/DNC
 00101        4*      C
 00103        5*            DIMENSION A(6), B(2)
 00104        6*            DATA A(1),A(2),A(3),A(4),A(5),A(6)/-0.1163143E+01, 0.2957672E+01,
 00104        7*           1     -0.3802650E+01, 0.2530089E+01, -0.8135335E+00, 0.9925338E-01/
 00104        8*           2     B(1),B(2)/-0.1577635E+00, -0.2297718E+00/
 00115        9*            IF(X.GT.2.5) GO TO 1
 00117       10*            DETA  = POLY(6,A,X)
 00120       11*            RETURN
 00121       12*          1 DETA  = B(1)*EXP(B(2)*X)
 00122       13*            RETURN
 00123       14*            END

      END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS SUBS
FOR S9A-07/25/72-23:01:39 (,0)

   FUNCTION POLY        ENTRY POINT 000036

   STORAGE USED: CODE(1) 000044; DATA(0) 000015; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000012 107G      0000   000003 INJP$     0000 I 000002 K         0000 I 000001 L         0000 R 000000 POLY


00101       1*              FUNCTION POLY(N,A,X)
00101       2*       C
00101       3*       C      EVALUATES POLYNOMIALS
00101       4*       C
00103       5*              DIMENSION A(N)
00104       6*              POLY = 0.
00105       7*              L = N
00106       8*              DO 1 K=1,N
00111       9*              POLY = POLY*X+A(L)
00112      10*            1 L = L-1
00114      11*              RETURN
00115      12*              END

      END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS SUB6
FOR S9A-07/25/72-23:01:48 (,0)

   SUBROUTINE RKS        ENTRY POINT 000643

   STORAGE USED: CODE(1) 001040; DATA(0) 000064; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR2$
    0004   NEXP5$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000010 10L     0001   000313 110L    0001   000333 120L    0001   000045 126G    0001   000343 130L
    0001   000071 140G    0001   000355 140L    0001   000105 146G    0001   000130 156G    0001   000417 160L
    0001   000150 164G    0001   000177 174G    0001   000500 185L    0001   000510 190L    0001   000013 20L
    0001   000232 205G    0001   000270 217G    0001   000524 220L    0001   000530 230L    0001   000543 240L
    0001   000374 243G    0001   000032 25L     0001   000552 250L    0001   000554 251L    0001   000572 257L
    0001   000604 259L    0001   000623 270L    0001   000456 300L    0001   000615 336G    0001   000054 40L
    0001   000060 45L     0001   000006 5L      0001   000076 50L     0001   000123 70L     0001   000135 80L
    0000 R 000014 AM      0000 R 000007 AMAX    0000 R 000011 C       0000 R 000010 D       0000 R 000001 DDT
    0000 R 000003 DELT    0000 R 000012 E       0000 R 000000 FR10    0000 I 000004 I       0000 I 000005 IFLAG
    0000   000030 INJP$   0000 I 000002 ISYMP   0000 I 000013 J       0000 R 000006 S


 00101          SUBROUTINE RKS(DERIV,CNTRL,Y,DY,A,R,T,DEL,N,IFVD,IBKP,NTRY,       DG000100
 00101         1IERR,DELY,PD,SD,YS,YST,DYST,YSIMP)                                DG000200
 00101      C
 00101      C   INTEGRATION
 00101      C
 00103          DIMENSION Y(N),DY(N),A(N),R(N),DELY(N),                           DG0  3
 00103         1PD(N),SD(N),YS(N),DYST(N),YST(N),YSIMP(N)                         DG000040
 00104          EXTERNAL  DERIV, CNTRL                                            DG000500
 00104      C   FR10 IS  FIFTH ROOT OF TEN                                        DG00 60
 00105          FR10=1.5848932                                                    DG000700
 00106          IERR=0                                                            DG000800
 00106      C     YS  CONTAINS Y VALUES AT LEFT END POINT OF INTEGRATION INTERVAL DG00090
 00106      C                                                                     DG001000
 00106      C     YSIMP CONTAINS Y FOR SIMPSONS RULE CHECK  CHECK NOT MADE FOR    DG001100
 00106      C         FIXED STEP MODE    ISYMP IS CONTROL PARAMETER =1,FIXED,2 VARDG00120
 00106      C                                                                     DG001300
 00106      C     IF FIXED STEP SIZE GO ONE INTERVAL OF LENGTH DELT AND RETURN TO DG00140
 00106      C        CNTRL, IF VAR GO TWO INTERVALS BEFORE RETURN TO CONTRL       DG00150
 00106      C                                                                     DG001600
 00106      C     IFVD  = 0    VARIABLE INTERVAL                                  DG00170
 00106      C           = 1    FIXED                                              DG001800
 00106      C     IBKP  = 0    CUT INTERVAL ONCE BEFORE REPEAT  (UNDER IFVD=0 )   DG00190
 00106      C           = 1    CUT AS REQUIRED                                    DG0 200
 00106      C     NTRY  = 1    CONTINUE INTEGRATING                               DG002100
```

```
00106     C                    2    RETURN FROM RKS                                    DG0 220
00106     C                    3    STEP REPEATED WITH NEW DELT                        DG002300
00106     C                    4    RESTART                                            DG00240
00106     C          IERR   =  0    NORMAL                                             DG002500
00106     C                   -1    DELT=0, RETURN FROM RKS                            DG002600
00106     C                    1    A(I)+ R(I)*ABS(Y(I)) = 0. , RETURN FROM RKS        DG002700
00107           5 IF(DEL) 20,10,20                                                     DG002800
00112          10 IERR=-1                                                              DG002900
00113             GO TO 270                                                            D7003000
00114          20 CALL DERIV(Y,DY,T)                                                   DG003100
00115             NTRY=1                                                               DG003200
00116             CALL CNTRL(Y,DY,DEL,T,NTRY,IFVD)                                     DG003300
00117          25 DOT=DEL                                                              DG003400
00120             IF(IFVD) 40,30,40                                                    DG003500
00123          30 ISYMP=2                                                              DG003600
00124             DELT=DEL/2.                                                          DG00370
00125             DO 31 I=1,N                                                          D7003800
00130          31 SD(I)=0.0                                                            DG00390
00132             IFLAG=1                                                              DG00400
00133             S=1.                                                                 DG004100
00134             GO TO 45                                                             DG004200
00135          40 ISYMP=1                                                              DG004300
00136             DELT=DEL                                                             DG00440
00137          45 DO 46 I=1,N                                                          DG004500
00142             YST(I)=Y(I)                                                          DG00460
00143          46 DYST(I)=DY(I)                                                        DG0 470
00145          50 DO 60 I=1,N                                                          DG004800
00150             DELY(I)=DELT*DY(I)                                                   DG004900
00151             PD(I)=DELY(I)                                                        DG00500
00152          60 CONTINUE                                                             DG005100
00154             GO TO (80,70),ISYMP                                                  DG005200
00155          70 DO 71 I=1,N                                                          DG005300
00160          71 SD(I)=SD(I)+S*DY(I)                                                  DG005400
00162          80 T=T+DELT/2.                                                          DG005500
00163             DO 85 I=1,N                                                          DG005600
00166             YS(I)=Y(I)                                                           DG00570
00167             Y(I)=YS(I)+DELY(I)/2.                                                DG005800
00170          85 CONTINUE                                                             DG005900
00172             CALL DERIV(Y,DY,T)                                                   DG006000
00173             DO 90 I=1,N                                                          DG006100
00176             DELY(I)=DELT*DY(I)                                                   DG00620
00177             PD(I)=PD(I)+2.*DELY(I)                                               DG006300
00200             Y(I)=YS(I)+DELY(I)/2.                                                DG00640
00201          90 CONTINUE                                                             DG006500
00203             CALL DERIV(Y,DY,T)                                                   DG006600
00204             DO 95 I=1,N                                                          DG00670
00207             DELY(I)=DELT*DY(I)                                                   DG00680
00210             PD(I)=PD(I)+2.*DELY(I)                                               DG006900
00211             Y(I)=YS(I)+DELY(I)                                                   DG00700
00212          95 CONTINUE                                                             DG007100
00214             T=T+DELT/2.                                                          DG007200
00215             CALL DERIV(Y,DY,T)                                                   DG00730
00216             DO 100 I=1,N                                                         DG007400
00221             DELY(I)=DELT*DY(I)                                                   DG007500
00222             PD(I)=PD(I)+DELY(I)                                                  DG00760
00223             Y(I)=YS(I)+PD(I)/6.                                                  DG00770
00224         100 CONTINUE                                                             DG007800
```

```
00226              GO TO (110,120),ISYMP                          DG007900
00227          110 NTRY=1                                         DG008000
00230              CALL DERIV(Y,DY,T)                             DG008100
00231              CALL CNTRL(Y,DY,DEL,T,NTRY,IFVD)               DG00820
00232              GO TO 300                                      DG008300
00233          120 GO TO (130,140),IFLAG                          DG008400
00234          130 S=4.                                           DG008500
00235              IFLAG=2                                        DG008600
00236              CALL DERIV(Y,DY,T)                             DG008700
00237              GO TO 50                                       D7008800
00240          140 CALL DERIV(Y,DY,T)                             DG008900
00241              AMAX =0.0                                      DG009000
00242              DO 180 I=1,N                                   DG009100
00245              SD(I)=SD(I)+DY(I)                              DG009200
00246              YSIMP(I)=YST(I)+DELT*SD(I)/3.                  DG009300
00247              D   =ABS(Y(I)-YSIMP(I))                        DG00940
00250              C   =A(I)+R(I)*ABS(Y(I))                       DG009500
00251              IF(C    ) 160,150,160                          DG00960
00254          150 IERR=1                                         DG009700
00255              GO TO 270                                      DG009800
00256          160 E   =ABS(D   /C    )                           DG009900
00257              AMAX=AMAX1(AMAX,E)                             DG01000
00260          180 CONTINUE                                       D7010100
00262              IF(AMAX-1.) 215,215,230                        DG01020
00265          215 NTRY= 1                                        DG010300
00266              CALL CNTRL(Y,DY,DEL,T,NTRY,IFVD)               DG010400
00267          300 IF(NTRY-1) 185,185,310                         DG01050
00272          310 IF(NTRY-2) 270,270,330                         DG01060
00275          330 IF(NTRY-3) 340,340,5                           DG01070
00300          340 T=T-DDT                                        DG01080
00301              IF(DEL) 259,10,259                             DG010900
00304          185 GO TO (40,190),ISYMP                           DG01100
00305          190 IF(AMAX-.75) 200,25,220                        DG011100
00310          200 IF(AMAX-.075) 210,25,25                        DG01120
00313          210 DEL=DEL*FR10                                   DG011300
00314              GO TO 25                                       DG011400
00315          220 DEL=DEL/FR10                                   DG011500
00316              GO TO 25                                       DG011600
00317          230 I =1+ IBKP                                     DG011700
00320              GO TO (240,250),I                              DG011800
00321          240 T=T-DEL                                        DG011900
00322              DEL=DEL/FR10                                   DG012000
00323              GO TO  259                                     DG01210
00324          250 J=1                                            DG012200
00325          251 AM=AMAX/10.**J                                 DG012300
00326              IF(1.-AM) 255,257,257                          DG01240
00331          255 J=J+1                                          DG012500
00332              GO TO 251                                      DG01260
00333          257 T=T-DEL                                        DG01270
00334              DEL=DEL/(FR10**J)                              DG01280
00335          259 DO 245 I=1,N                                   DG01290
00340              DY(I)=DYST(I)                                  DG013000
00341          245 Y(I)=YST(I)                                    DG013100
00343              GO TO 25                                       DG013200
00344          270 RETURN                                         DG013300
00345              END                                            DG013400
```

```
END OF COMPILATION:        NO  DIAGNOSTICS.
```
2

```
@ XQT
MAP 0023-07/25-23:02

ADDRESS LIMITS    001000 013206      040000 044714
STARTING ADDRESS  012523

WORDS DECIMAL        5255 IBANK         2509 DBANK


                  SEGMENT MAIN           001000 013206      040000 044714

NSWTC$/FOR                    1    001000 001021
NRBLK$/FOR                    1    001022 001044
NRWND$/FOR                    1    001045 001124      2    040000 040011
NWEF$/FOR                     1    001125 001326      2    040012 040031
NFTCH$/FOR                    1    001327 001617      2    040032 040067
NBDCV$/FOR                    1    001620 001752      2    040070 040125
NFTV$/FOR                     1    001753 001775
NCNVT$/FOR                    1    001776 002222      2    040126 040215
NCLOS$/FOR                    1    002223 002371      2    040216 040247
NWBLK$/FOR                    1    002372 002513
NBSBL$/FOR                    1    002514 002550
NUPDA$/FOR                    1    002551 002603
NBF00$/FOR                                            2    040250 042451
NININ$/FOR                    1    002604 003014      2    042452 042463
NINPT$/FOR                    1    003015 003657      2    042464 042503
NOTIN$/FOR                    1    003660 004173      2    042504 042507
NOUT$/FOR                     1    004174 005162      2    042510 042534
NFMT$/FOR                     1    005163 006041      2    042535 042611
NIOER$/FOR                    1    006042 006214      2    042612 042716
NFCHK$/FOR                    1    006215 007076      2    042717 043055
                                                      4    043056 043127
NTAB$/FOR                                             2    043130 043166
ERU$/MISC
NIBJF$/FOR                    1    007077 007141      2    043167 043167
TIR$/TECH                     1    007142 007626      0    043170 043220
                                                      2    043221 043500
SQRT$/FOR                     1    007627 007667      2    043501 043512
ASINCOS$/FOR                  1    007670 010104      0    043513 043540
NIER$/FOR                     1    010105 010166      2    043541 043674
NOBJF$/FOR                    1    010167 010233
EXP$/FOR                      1    010234 010323      2    043675 043715
NEXP5$/FOR                    1    010324 010411      2    043716 043725
NERR$/FOR                     1    010412 010736      2    043726 044071
SDR (COMMON BLOCK)                                         044072 044105
MCT (COMMON BLOCK)                                         044106 044113
SDC (COMMON BLOCK)                                         044114 044116
BLANK$COMMON (COMMON BLOCK)
SUB6                          1    010737 011776      0    044117 044202
                                                      2    BLANK$COMMON
```

SUB5	1	011777 012042	0	044203 044217
			2	BLANK$COMMON
SUB4	1	012043 012106	0	044220 044240
			2	BLANK$COMMON
SUB3	1	012107 012152	0	044241 044262
			2	BLANK$COMMON
SUB2	1	012153 012345	0	044263 044300
	3	SDC	2	BLANK$COMMON
			4	MCT
SUB1	1	012346 012522	0	044301 044337
	3	SDR	2	BLANK$COMMON
			4	SDC
MAIN	1	012523 013206	0	044340 044714
	3	SDR	2	BLANK$COMMON
			4	MCT

SYS$*RLIB$. LEVEL 63
END OF COLLECTION - TIME 1.677 SECONDS

APPENDIX B

COMPUTER CODE FOR MINIMUM AREA OPTIMIZATION

```
2   @FOR,IS MAIN
    FOR S9A-07/27/72-17:43:15 (,0)

     MAIN PROGRAM

     STORAGE USED: CODE(1) 001045; DATA(0) 000677; BLANK COMMON(2) 000000

      COMMON BLOCKS:

      0003    BLKI     000004
      0004    BLKD     000002
      0005    VCT      000005
      0006    BLKR     000002
      0007    BLKJ     000002

     EXTERNAL REFERENCES (BLOCK, NAME)

      0010    SERV
      0011    SCNTL
      0012    REST
      0013    NDERV
      0014    ETA
      0015    DETA
      0016    NDDERV
      0017    NDER
      0020    INITIAL
      0021    INTMIX
      0022    RKS
      0023    FMINV
      0024    ENDCND
      0025    RESCND
      0026    NINTR$
      0027    NRDU$
      0030    NI02$
      0031    NWDU$
      0032    ASIN
      0033    SQRT
      0034    NI01$
      0035    NSTOP$

     STORAGE ASSIGNMENT (BLOCK, TYPE, RELATIVE LOCATION, NAME)

      0001   000002 1L        0001   000163 100L      0000   000421 1000F     0001   000333 105L      0001   000351 108L
      0001   000354 109L      0001   000361 110L      0000   000423 2000F     0000   000454 2010F     0000   000467 2040F
      0000   000505 205F      0000   000622 2050F     0000   000616 2070F     0001   001033 2080L     0000   000631 2085F
      0000   000514 210F      0000   000521 215F      0000   000602 220F      0000   000533 230F      0001   000516 233G
      0000   000547 240F      0000   000564 250F      0001   001024 300L      0001   001041 3000L     0001   000725 340G
      0001   000020 50L       0001   000160 90L       0000   000462 900F      0000 R 000050 A         0000 R 000337 AM
      0000 R 000353 ASTA      0000 R 000362 AYY       0004   000003 A1        0004   000004 A2        0004   000005 A3
      0004   000006 A4        0004   000007 A5        0004   000010 A6        0000 R 000363 BYY       0015 R 000000 DETA
      0000 R 000367 DETZ      0003   000023 DE1DL     0003   000021 DE4DTB    0003 R 000013 DFM       0003 R 000012 DFMX
      0003 R 000010 DFNX      0006 R 000006 DLDNCB    0006 R 000001 DLDU      0006 R 000002 DLDV      0005 R 000000 DLMT
      0000 R 000120 DLY       0007   000000 DNCBDU    0007   000001 DNCBDV    0003 R 000007 DNCDT1    0000 R 000405 DX
      0005 R 000003 DXWRT     0000 R 000024 DY        0000 R 000240 DYST      0000 R 000370 DYY       0000 R 000373 D2CD2T
```

```
0000 R 000374 D2CTNB     0000 R 000402 D2E4LN     0000 R 000376 D2E4LU     0000 R 000400 D2E4LV     0000 R 000401 D2E4TN
0000 R 000375 D2E4TU     0000 R 000377 D2E4TV     0003 R 000016 D2FMLL     0006 R 000003 D2LDUU     0006 R 000004 D2LDUV
0006 R 000005 D2LDVV     0006 R 000007 D2LNCB     0006 R 000010 D2LUNB     0006 R 000011 D2LVNB     0003 R 000015 D2MDNC
0003 R 000014 D2MLNC     0003 R 000011 D2NDLL     0004 R 000001 D3M2LN     0004 R 000002 D3M2NL     0004   000011 EB
0014 R 000000 ETA        0000 R 000365 ETY        0000 R 000364 ETYY       0003   000022 E3       0003 R 000002 FM
0003 R 000003 FN         0003 R 000005 FNC        0003 R 000004 FNCBR      0000 I 000403 I          0000 I 000410 IAKP
0005 I 000001 ICNT       0000 I 000412 IERR       0000 I 000406 IFVD       0000 I 000413 LCNT       0005 I 000004 LSTEP
0000 I 000407 N          0000 I 000357 NCT        0000 I 000354 NIT        0000 I 000414 NITMAX     0000 I 000411 NTRY
0000 R 000144 PD         0000 R 000074 R          0000 R 000355 RHOD       0006 R 000000 RLAM       0011 R 000000 SCNTL
0000 R 000170 SD         0010 R 000000 SDRV       0003 R 000000 THETAB     0000 R 000372 THETAF     0003 R 000001 THETAS
0000 R 000356 TH4        0000 R 000360 T2         0000 R 000361 T3         0004 R 000000 U          0003 R 000006 V
0000 R 000334 XM         0005 R 000002 XWRT       0000 R 000000 Y          0000 R 000214 YS         0000 R 000310 YSIMP
0000 R 000264 YST        0000 R 000366 YY         0003 R 000017 Y1         0003 R 000020 Y2         0000 R 000371 ZZ
0000 R 000404 ZZZ        0000 R 000415 Z1         0000 R 000416 Z2         0000 R 000417 Z3         0000 R 000420 Z5
```

```
00100          C
00100          C      RADIATOR SYSTEMS OPTIMIZATION FOR MINIMUM AREA
00100          C
00101                 EXTERNAL SDRV,SCNTL
00103                 DIMENSION Y(20),DY(20),A(20),R(20),DLY(20),PD(20),SD(20),
00103                1          YS(20),DYST(20),YST(20),YSIMP(20),XM(3),AM(3,4)
00104                 COMMON /BLKI/THETAB,THETAS,FM,FN,FNCBR,FNC,V,DNCDT1,DFNX,D2NDLL,
00104                1              DFMX,DFM,D2MLNC,D2MDNC,D2FMLL,Y1,Y2,DE4DTB,E3,DE1DL/
00104                2         BLKD/U,D3M2LN,D3M2NL,A1,A2,A3,A4,A5,A6,EB
00104                3         /MCT/DLMT,ICNT,XWRT,DXWRT,LSTEP
00104                4         /BLKP/RLAM,DLDU,DLDV,D2LDUU,D2LDUV,D2LDVV,DLDNCB,
00104                5              D2LNCB,D2LUNB,D2LVNB
00104                6         /BLKB/DNCBDU,DNCBDV
00105                 FFS(X)  = (SQRT(X*(X+2.0))+ASIN(1.0/(X+1.0))-1.570796)/X
00106                 FFN(X,Y)= 1.0-Y*(0.1460*Y-0.02866)/X
00107                 DFFN(X,Y)=(-0.2920*Y+0.02866)/X
00110              1  READ(5,1000,END=3000) THETAS,U,V,FNCBR,ASTAR,DXWRT
00120           1000  FORMAT(5F16.8)
00121                 NIT     =  1
00122              5  IF (U.LT.4.00E-06.OR.U.GT.250.1) GO TO 1
00124                 IF (V.LT.4.00E-05.OR.V.GT.50.01) GO TO 1
00126                 IF(FNCBR.LT.0.00009.OR.FNCBR.GT.4.01) GO TO 1
00130              5, CALL REST(U,V,ASTAR,RLAM,DLDU,DLDV,D2LDUU,D2LDUV,D2LDVV,
00130                1DLDNCB,D2LNCB,D2LUNB,D2LVNB)
00131                 CALL NDERV(RLAM,FN,DFNX,D2NDLL)
00132                 RHOD    = RLAM
00133                 WRITE(6,2000) THETAS,ASTAR,U,V,FNCBR,RLAM
00143           2000, FORMAT (1H1,10X,10HTHETA-S = F20.8/
00143                4              11X,10H  ASTAR = F20.6//
00143                1              11X,10H      U = F20.6/
00143                2              11X,10H      V = F20.6/
00143                3              11X,10H  FNCBR = F20.6/
00143                5              11X,10H LAMBDA = F20.6///)
00144                 WRITE(6,2010) NIT
00147           2010  FORMAT (5X'NUMBER OF ITERATIONS = 'I2)
00150                 TH4     = THETAS**4
00151                 IF(V.GT.0.2) GO TO 90
00153                 IF(V.LE.1.0E-10) GO TO 108
00155             90  THETAB  = 0.9
```

```
  95 NCT       = 0
 100 T2        = THETAB**2
     T3        = T2*THETAB
     FNC       = FNCBR*T3
     FM        = FFN(RHOD,FNC)*FFS(RHOD)
     DFM       = DFFN(RHOD,FNC)*FFS(RHOD)
     AYY       = T3*THETAB-TH4
     BYY       = 1.0-THETAB
     ETYY      = ETA(FNC)
     ETY       = ETYY*FM+FM
     YY        = 1.0/V-ETY*AYY/BYY
     DETZ      = (DFM*ETYY+FM*DETA(FNC))*3.0*T2*FNCBR
     DYY       = -AYY/BYY*(DETZ+ETY/BYY)-4.0*ETY*T3/BYY
     ZZ        = THETAB-YY/DYY
     IF(NCT.GT.20) GO TO 109
     IF(ZZ.LT.1.0) GO TO 105
     THETAB  = (THETAB+1.0)/2.0
     NCT     = NCT+1
     GO TO 100
 105 IF(ABS(ZZ-THETAB)/ZZ.LT.1.0E-06) GO TO 110
     NCT            = NCT+1
     THETAB  = ZZ
     GO TO 100
 108 THETAB         = 1.0
     GO TO 110
 109 WRITE(6,900)
C
 110 Y(1)      = 1.0
     Y(2)      = THETAB
 900 FORMAT(1H0,20HNEWTON-RAPHSON FAILS)
     THETAF  = Y(1)
     Y1        = Y(1)
     Y2        = Y(2)
       CALL NCDERV(FNCBR,THETAB,FNC,DNCDT1,D2CD2T,D2CTNB)
     CALL MDER(RLAM,FNC,FM,DFMX,DFM,D2FMLL,D2MDNC,D2MLNC,D3M2LN,D3M2NL)
     CALL INTIAL(DLDU,D2LDUU,Y(3),Y(4),Y(5),Y(6),0.,1.,D2E4TU,D2E4LU)
     CALL INTIAL(DLDV,D2LDVV,Y(7),Y(8),Y(9),Y(10),0.,0.,D2E4TV,D2E4LV)
     CALL INTIAL(DLDNCB,D2LNCB,Y(11),Y(12),Y(13),Y(14),1.,1.,D2E4TN,
    1                D2E4LN)
     CALL INTMIX(D2E4TV,Y(4),DLDU,D2E4LV,D2LDUV,Y(16),Y(15))
     CALL INTMIX(D2E4TN,Y(4),DLDU,D2E4LN,D2LUNB,Y(18),Y(17))
     CALL INTMIX(D2E4TN,Y(8),DLDV,D2E4LN,D2LVNB,Y(20),Y(19))
     DO 115 I=1,20
     A(I)      = 1.0E-05
 115 R(I)      = 1.0E-05
C
     WRITE(6,2040)
2040 FORMAT(/7X,6HTHETAF,9X,6HTHETAB,9X,2HNC,13X,6HETABAR,
    1               9X,3HETA,13X,1HM,14X,1HN,14X,4HZETA/)
C
     ZZZ       = 0.0
     DX        = 1.0/(U*(1.0-THETAB))
     IFVD      = 0
     IF(DX.GT.DXWRT) DX = DXWRT
     N         = 20
     IBKP      = 1
     NTRY      = 1
```

```
00253              IERR     = 0
00253        C
00254              DLMT     = DXWRT/500.0
00255              XWRT     = 0.0
00256              LSTEP    = 0
00257              LCNT     = 0
00260              ICNT     = 0
00261              CALL RKS(SDRV,SCNTL,Y,DY,A,R,ZZZ,DX,N,IFVD,IBKP,NTRY,IERR,
00261             1         DLY,PD,SD,YS,YST,DYST,YSIMP)
00262              XM(1)    =  -Y(3)
00263              XM(2)    =  -Y(7)
00264              XM(3)    = -Y(11)
00265              AM(1,1) =  Y(5)
00266              AM(1,2) =  Y(15)
00267              AM(1,3) =  Y(17)
00270              AM(2,1) =  Y(15)
00271              AM(2,2) =  Y(9)
00272              AM(2,3) =  Y(19)
00273              AM(3,1) = Y(17)
00274              AM(3,2) = Y(19)
00275              AM(3,3) = Y(13)
00276              CALL FMINV(AM,XM,3,4)
00277              WRITE (6,205)
00301        205   FORMAT (///45X,27H PARAMETERS AT END OF TUBE //)
00302              WRITE (6,210) Y(1)
00305        210   FORMAT (1X,51X,8HTHETAE =,F10.6,/)
00306              WRITE (6,215) U,V,ENCBR
00313        215   FORMAT (1X,23X,3HU =,E14.6,16X,3HV =,E14.6,12X,7HNCBAR =,E14.6,/)
00314              WRITE (6,230) Y(3),Y(7),Y(11)
00321        230   FORMAT (1X,19X,7HDTFDU =,E14.6,12X,7HDTFDV =,E14.6,9X,
00321             1         10HDTFNCBAR =,E14.6,/)
00322              WRITE (6,240) Y(5),Y(9),Y(13)
00327        240   FORMAT (1X,17X,9HD2TFD2U =,E14.6,10X,9HD2TFD2V =,E14.6,6X,
00327             1         13HD2TFD2NCBAR =,E14.6,/)
00330              WRITE (6,250) Y(15),Y(17),Y(19)
00335        250   FORMAT (1X,16X,10HD2TFDUDV =,E14.6,5X,14HD2TFDUDNCBAR =,E14.6,
00335             1         5X,14HD2TFDVDNCBAR =,E14.6,/)
00336              WRITE(6,220) (XM(I),I=1,3)
00344        220   FORMAT (/19X9HDELTA U =,E14.6,10X,9HDELTA V =,E14.6,6X,
00344             1          13HDELTA NCBAR =,E14.6/)
00345              NITMAX = 20
00346        200   IF (NIT.GT.NITMAX) GO TO 300
00350              NIT      =  NIT+1
00351              Z1       = U
00352              Z2       = V
00353              Z3       = ENCBR
00354              CALL BNDCND(Y,U,V,ENCBR,YM)
00355              CALL RESBND(U,V,XM,ASTAR)
00356              Z5       = Y(1)-THETAS
00357              IF(Z5.LT.0.0001) GO TO 2080
00361              IF (ABS(XM(1))/Z1.GT.0.0001) GO TO 50
00363              IF (ABS(XM(2))/Z2.GT.0.0001) GO TO 50
00365              IF(ABS(XM(3))/Z3.GT.0.0001) GO TO 50
00367              WRITE(6,2070)
00371        2070  FORMAT(1H0,15HOPTIMUM REACHED)
00372              GO TO 1
00373        300   WRITE(6,2050) NITMAX
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00376     154*     2050 FORMAT (1X,30H NUMBER OF ITERATIONS EXCEEDS ,I2)
00377     155*          GO TO 1
00400     156*     2080 WRITE(6,2085)
00402     157*     2085 FORMAT(1H0,24HVANISHING HEAT REJECTION)
00403     158*          GO TO 1
00404     159*     3000 STOP
00405     160*          END

         END OF COMPILATION:          NO  DIAGNOSTICS.
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@FOR,IS RKS
FOR S9A-07/27/72-17:43:28 (,0)

   SUBROUTINE RKS        ENTRY POINT 000643

   STORAGE USED: CODE(1) 001040; DATA(0) 000064; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR2$
    0004   NEXP5$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000010 10L      0001   000313 110L     0001   000333 120L     0001   000045 126G     0001   000343 130L
    0001   000071 140      0001   000355 140L     0001   000105 146G     0001   000130 156G     0001   000417 160L
    0001   000150 164      0001   000177 174G     0001   000500 185L     0001   000510 190L     0001   000013 20L
    0001   000232 205      0001   000270 217G     0001   000524 220L     0001   000530 230L     0001   000543 240L
    0001   000374 243      0001   000032 25L      0001   000552 250L     0001   000554 251L     0001   000572 257L
    0001   000604 259      0001   000623 270L     0001   000456 300L     0001   000615 336G     0001   000054 40L
    0001   000060 45L      0001   000006 5L       0001   000076 50L      0001   000123 70L      0001   000135 80L
    0000 R 000014 AM       0000 R 000007 AMAX     0000 R 000011 C        0000 R 000010 D        0000 R 000001 DDT
    0000 R 000003 DELT     0000 R 000012 F        0000 R 000000 FR10     0000 I 000004 I        0000 I 000005 IFLAG
    0000   000030 INJ$     0000 I 000002 ISYMP    0000 I 000013 J        0000 R 000006 S


 00101      1*             SUBROUTINE RKS(DERIV,CNTPL,Y,DY,A,R,T,DEL,N,IFVD,IBKP,NTRY,
 00101      2*            1IERR,DELY,PD,SD,YS,YST,DYST,YSIMP)                               DG00020
 00103      3*             DIMENSION Y(N),DY(N),A(N),R(N),DELY(N),                          DG0  3
 00103      4*            1PD(N),SD(N),YS(N),DYST(N),YST(N),YSIMP(N)                        DG00040
 00104      5*             EXTERNAL  DERIV, CNTRL                                           DG000500
 00104      6*     C       FR10 IS  FIFTH ROOT OF TEN                                       DG00 60
 00105      7*             FR10=1.5848932                                                   DG000700
 00106      8*             IERR=0                                                           DG000800
 00106      9*     C         YS  CONTAINS Y VALUES AT LEFT END POINT OF INTEGRATION INTERVAL DG00090
 00106     10*     C                                                                        DG001000
 00106     11*     C         YSIMP CONTAINS Y FOR SIMPSON'S RULE CHECK  CHECK NOT MADE FOR     DG001100
 00106     12*     C              FIXED STEP MODE    ISYMP IS CONTROL PARAMETER =1,FIXED,2 VARDG00120
 00106     13*     C                                                                        DG001300
 00106     14*     C         IF FIXED STEP SIZE GO ONE INTERVAL OF LENGTH DELT AND RETURN TO DG00140
 00106     15*     C            CNTRL, IF VAR GO TWO INTERVALS BEFORE RETURN TO CONTRL       DG00150
 00106     16*     C                                                                        DG001600
 00106     17*     C         IFVD   = 0      VARIABLE INTERVAL                              DG00170
 00106     18*     C                = 1      FIXED                                          DG001800
 00106     19*     C         IBKP   = 0      CUT INTERVAL ONCE BEFORE REPEAT  (UNDER IFVD=0 ) DG00190
 00106     20*     C                = 1      CUT AS REQUIRED                                DG0 200
 00106     21*     C         NTRY   = 1      CONTINUE INTEGRATING                           DG002100
 00106     22*     C                  2      RETURN FROM RKS                                DG0 220
 00106     23*     C                  3      STEP REPEATED WITH NEW DELT                    DG002300
 00106     24*     C                  4      RESTART                                        DG00240
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00106      C         IERR  = 0    NORMAL                                        DG002500
00106      C               -1     DELT=0, RETURN FROM RKS                       DG002600
00106      C                1     A(I)+ R(I)*ABS(Y(I)).= 0. , RETURN FROM RKS   DG002700
00107           5 IF(DEL) 20,10,20                                              DG002800
00112          10 IERR=-1                                                       DG002900
00113             GO TO 270                                                     DG003000
00114          20 CALL DERIV(Y,DY,T)                                            DG003100
00115             NTRY=1                                                        DG003200
00116             CALL CNTRL(Y,DY,DEL,T,NTRY,IFVD)                              DG003300
00117          25 DDT=DEL                                                       DG003400
00120             IF(IFVD) 40,30,40                                             DG003500
00123          30 ISYMP=2                                                       DG003600
00124             DELT=DEL/2.                                                   DG003700
00125             DO 31 I=1,N                                                   DG003800
00130          31 SD(I)=0.0                                                     DG003900
00132             IFLAG=1                                                       DG004000
00133             S=1.                                                          DG004100
00134             GO TO 45                                                      DG004200
00135          40 ISYMP=1                                                       DG004300
00136             DELT=DEL                                                      DG004400
00137          45 DO 46 I=1,N                                                   DG004500
00142          46 YST(I)=Y(I)                                                   DG004600
00143          47 DYST(I)=DY(I)                                                 DG004700
00145          50 DO 60 I=1,N                                                   DG004800
00150             DELY(I)=DELT*DY(I)                                            DG004900
00151             PD(I)=DELY(I)                                                 DG005000
00152          60 CONTINUE                                                      DG005100
00154             GO TO (80,70),ISYMP                                           DG005200
00155          70 DO 71 I=1,N                                                   DG005300
00160          71 SD(I)=SD(I)+S*DY(I)                                           DG005400
00162          80 T=T+DELT/2.                                                   DG005500
00163             DO 85 I=1,N                                                   DG005600
00166             YS(I)=Y(I)                                                    DG005700
00167             Y(I)=YS(I)+DELY(I)/2.                                         DG005800
00170          85 CONTINUE                                                      DG005900
00172             CALL DERIV(Y,DY,T)                                            DG006000
00173             DO 90 I=1,N                                                   DG006100
00176             DELY(I)=DELT*DY(I)                                            DG006200
00177             PD(I)=PD(I)+2.*DELY(I)                                        DG006300
00200             Y(I)=YS(I)+DELY(I)/2.                                         DG006400
00201          90 CONTINUE                                                      DG006500
00203             CALL DERIV(Y,DY,T)                                            DG006600
00204             DO 95 I=1,N                                                   DG006700
00207             DELY(I)=DELT*DY(I)                                            DG006800
00210             PD(I)=PD(I)+2.*DELY(I)                                        DG006900
00211             Y(I)=YS(I)+DELY(I)                                            DG007000
00212          95 CONTINUE                                                      DG007100
00214             T=T+DELT/2.                                                   DG007200
00215             CALL DERIV(Y,DY,T)                                            DG007300
00216             DO 100 I=1,N                                                  DG007400
00221             DELY(I)=DELT*DY(I)                                            DG007500
00222             PD(I)=PD(I)+DELY(I)                                           DG007600
00223             Y(I)=YS(I)+PD(I)/6.                                           DG007700
00224         100 CONTINUE                                                      DG007800
00226             GO TO (110,120),ISYMP                                         DG007900
00227         110 NTRY=1                                                        DG008000
00230             CALL DERIV(Y,DY,T)                                            DG008100
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00231          CALL CNTRL(Y,DY,DEL,T,NTRY,IFV)              DG008200
00232          GO TO 300                                    DG008300
00233    120   GO TO (130,140),IFLAG                        DG008400
00234    130   S=4.                                         DG008500
00235          IFLAG=2                                      DG008600
00236          CALL DERIV(Y,DY,T)                           DG008700
00237          GO TO 50                                     DG008800
00240    140   CALL DERIV(Y,DY,T)                           DG008900
00241          AMAX =0.0                                    DG009000
00242          DO 180 I=1,N                                 DG009100
00245          SD(I)=SD(I)+DY(I)                            DG009200
00246          YSIMP(I)=YST(I)+DELT*SD(I)/3.                DG009300
00247          D    =ABS(Y(I)-YSIMP(I))                     DG009400
00250          C    =A(I)+B(I)*ABS(Y(I))                    DG009500
00251          IF(C    ) 160,150,160                        DG009600
00254    150   IERR=1                                       DG009700
00255          GO TO 270                                    DG009800
00256    160   E    =ABS(D    /C    )                       DG009900
00257          AMAX=AMAX1(AMAX,E)                           DG010000
00260    180   CONTINUE                                     DG010100
00262          IF(AMAX-1.) 215,215,230                      DG010200
00265    215   NTRY= 1                                      DG010300
00266          CALL CNTRL(Y,DY,DEL,T,NTRY,IFV)              DG010400
00267    300   IF(NTRY-1) 185,185,310                       DG010500
00272    310   IF(NTRY-2) 270,270,330                       DG010600
00275    330   IF(NTRY-3) 340,340,5                         DG010700
00300    340   T=T-DDT                                      DG010800
00301          IF(DEL) 259,10,259                           DG010900
00304    185   GO TO (40,190),ISYMP                         DG011000
00305    190   IF(AMAX-.75) 200,25,220                      DG011100
00310    200   IF(AMAX-.075) 210,25,25                      DG011200
00313    210   DEL=DEL*FR10                                 DG011300
00314          GO TO 25                                     DG011400
00315    220   DEL=DEL/FR10                                 DG011500
00316          GO TO 25                                     DG011600
00317    230   I =1+ IBKP                                   DG011700
00320          GO TO (240,250),I                            DG011800
00321    240   T=T-DEL                                      DG011900
00322          DEL=DEL/FR10                                 DG012000
00323          GO TO  259                                   DG012100
00324    250   J=1                                          DG012200
00325    251   AM=AMAX/10.**J                               DG012300
00326          IF(1.-AM) 255,257,257                        DG012400
00331    255   J=J+1                                        DG012500
00332          GO TO 251                                    DG012600
00333    257   T=T-DEL                                      DG012700
00334          DEL=DEL/(FR10**J)                            DG012800
00335    259   DO 245 I=1,N                                 DG012900
00340          DY(I)=DYST(I)                                DG013000
00341    245   Y(I)=YST(I)                                  DG013100
00343          GO TO 25                                     DG013200
00344    270   RETURN                                       DG013300
00345          END                                          DG013400

        END OF COMPILATION:        NO  DIAGNOSTICS.
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@FOR,IS SDRV
FOR S9A-07/27/72-17:43:39 (,0)

     SUBROUTINE SDRV      ENTRY POINT 000601

     STORAGE USED: CODE(1) 000605; DATA(0) 000066; BLANK COMMON(2) 000000

      COMMON BLOCKS:

      0003    BLKI     00002[illegible]
      0004    BLKD     00001[illegible]
      0005    BLKR     00001[illegible]
      0006    VAB      0000[illegible]

     EXTERNAL REFERENCES (BLOCK, NAME)

      0007    ETA
      0010    NCDERV
      0011    MDER
      0012    DETA
      0013    DERV
      0014    MIXDER
      0015    NERR3$

     STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

      0000 R 000003 AAA     0004   000003 A1      0004   000004 A2      0004   000005 A3      0004   000006 A4
      0004   000007 A5      0004   000010 A6      0000 R 000005 BBB     0000 R 000037 DA1DN   0000 R 000007 DA1DU
      0000 R 000023 DA1DV   0000 R 000040 DA2DN   0000 R 000010 DA2DU   0000 R 000024 DA2DV   0000 R 000041 DA3DN
      0000 R 000011 DA3DU   0000 R 000025 DA3DV   0000 R 000042 DA4DN   0000 R 000012 DA4DU   0000 R 000026 DA4DV
      0000 R 000043 DA5DN   0000 R 000013 DA5DU   0000 R 000027 DA5DV   0000 R 000044 DA6DN   0000 R 000014 DA6DU
      0000 R 000030 DA6DV   0000 R 000045 DEBDN   0000 R 000004 DEBDTB  0000 R 000015 DEBDU   0000 R 000031 DEBDV
      0000 R 000046 DEN     0000 R 000047 DEPN    0000 R 000017 DEPU    0000 R 000033 DEPV    0012 R 000000 DETA
      0000 R 000016 DEU     0000 R 000032 DEV     0003   000023 DF1DL   0003   000021 DF4DTR  0003 R 000013 DFM
      0003 R 000012 DFMX    0003   000010 DFNX    0005 R 000006 DLDNCB  0005 R 000001 DLDU    0005 R 000002 DLDV
      0000 R 000050 DMDN    0000 R 000020 DMDU    0000 R 000034 DMDV    0000 R 000036 DNCDN   0003 R 000007 DNCDT1
      0000 R 000006 DNCDU   0000 R 000022 DNCDV   0000 R 000001 D2CD2T  0000 R 000002 D2CTNB  0003 R 000016 D2FMLL
      0005 R 000003 D2LDUU  0005 R 000004 D2LDUV  0005 R 000005 D2LDVV  0005 R 000007 D2LNCB  0005 R 000010 D2LUNB
      0005 R 000011 D2LVN   0003 R 000015 D2MDNC  0003 R 000014 D2MLNC  0000 R 000051 D2MNCN  0000 R 000021 D2MNCU
      0000 R 000035 D2MNCV  0003   000011 D2NDLL  0004 R 000001 D3M2LN  0004 R 000002 D3M2NL  0004 R 000011 EB
      0006 R 000002 ET      0007 R 000000 ETA     0003   000022 E3      0003 R 000002 FM      0003 R 000003 FN
      0003 R 000005 FNC     0003 R 000004 FNCBR   0000   000056 INJP$   0005 R 000000 RLAM    0003 R 000000 THETAB
      0000 R 000000 THETAF  0003 R 000001 THETAS  0004 R 000000 U       0003   000006 V       0003 R 000017 Y1
      0003 R 000020 Y2      0006 R 000000 Z1      0006 R 000001 Z2

00101      1*          SUBROUTINE SDRV(Y,DY,X)
00101      2*     C
00101      3*     C    CALCULATION OF DERIVATIVES FOR THE INTEGRATION SUBROUTINE
00101      4*     C
00103      5*          DIMENSION Y(20),DY(20)
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00104      COMMON /BLKI/THETAB,THETAS,FM,FN,FNCBR,FNC,V,DNCDT1,DFNX,D2NDLL,
00104     1           DFMX,DFM,D2MLNC,D2MDNC,D2FMLL,Y1,Y2,DE4DTB,E3,DE1DL/
00104     2      BLKD/U,D3M2LN,D3M2NL,A1,A2,A3,A4,A5,A6,EB
00104     3      /BLKR/RLAM,DLDU,DLDV,D2LDUU,D2LDUV,D2LDVV,DLDNCB,
00104     4           D2LNCB,D2LUNB,D2LVNB
00104     5      /VAB/ Z1,Z2,ET
00105       Z1        = FNC
00106       Z2        = FM*ETA(FNC)+FN
00107       ET        = ETA(FNC)
00110       THETAE    = Y(1)
00111       THETAB    = Y(2)
00112       Y1        = Y(1)
00113       Y2        = Y(2)
00114       CALL NCDERV(FNCBR,THETAB,FNC,DNCDT1,D2CD2T,D2CTNB)
00115       CALL MDER(RLAM,FNC,FM,DFMX,DFM,D2FMLL,D2MDNC,D2MLNC,D3M2LN,D3M2NL)
00116       AAA       = THETAE-THETAB
00117       DY(1)     = -U*AAA
00120       EB        = FM*ETA(FNC)+FN
00121       DEBDTB    = 3*THETAB**2*FNCBR*(FM*DETA(FNC)+ETA(FNC)*DFM)
00122       BBB       = 4*THETAB**3/(THETAE**4-THETAS**4)
00123       DY(2)     = -U/(1/AAA+DEBDTB/EB+BBB)
00124       CALL DERV(Y(3),Y(4),Y(5),Y(6),DLDU,D2LDUU,DY(3),DY(4),DY(5),
00124     1           DY(6),0.,1.,DNCDU,DA1DU,DA2DU,DA3DU,DA4DU,DA5DU,
00124     2           DA6DU,DEBDU,DEU,DEPU,DMDU,D2MNCU)
00125       CALL DERV(Y(7),Y(8),Y(9),Y(10),DLDV,D2LDVV,DY(7),DY(8),DY(9),
00125     1           DY(10),0.,0.,DNCDV,DA1DV,DA2DV,DA3DV,DA4DV,DA5DV,
00125     2           DA6DV,DEBDV,DEV,DEPV,DMDV,D2MNCV)
00126       CALL DERV(Y(11),Y(12),Y(13),Y(14),DLDNCB,D2LNCB,DY(11),DY(12),
00126     1           DY(13),DY(14),1.,0.,DNCDN,DA1DN,DA2DN,DA3DN,DA4DN,
00126     2           DA5DN,DA6DN,DEBDN,DEN,DEPN,DMDN,D2MNCN)
00127       CALL MIXDER(Y(4),Y(8),Y(7),Y(16),Y(15),DNCDU,DNCDV,DY(4),DA1DU,
00127     1              DA1DV,DA2DU,DA2DV,DA3DU,DA3DV,DA4DV,DA5DU,DA5DV,
00127     2              DA6DU,DA6DV,DLDU,DLDV,D2LDUV,DEBDV,DEBDU,DEU,DEV,
00127     3              DEPU,DEPV,DMDU,DMDV,D2MNCU,D2MNCV,1.,0.,DY(16),
00127     4              DY(15))
00130       CALL MIXDER(Y(4),Y(12),Y(11),Y(18),Y(17),DNCDU,DNCDN,DY(4),
00130     1              DA1DU,DA1DN,DA2DU,DA2DN,DA3DU,DA3DN,DA4DN,DA5DU,
00130     2              DA5DN,DA6DU,DA6DN,DLDU,DLDNCB,D2LUNB,DEBDN,DEBDU,
00130     3              DEU,DEN,DEPU,DEPN,DMDU,DMDN,D2MNCU,D2MNCN,1.,1.,
00130     4              DY(18),DY(17))
00131       CALL MIXDER(Y(8),Y(12),Y(11),Y(20),Y(19),DNCDV,DNCDN,DY(8),
00131     1              DA1DV,DA1DN,DA2DV,DA2DN,DA3DV,DA3DN,DA4DN,DA5DV,
00131     2              DA5DN,DA6DV,DA6DN,DLDV,DLDNCB,D2LVNB,DEBDN,DEBDV,
00131     3              DEV,DEN,DEPV,DEPN,DMDV,DMDN,D2MNCV,D2MNCN,0.,1.,
00131     4              DY(20),DY(19))
00132       RETURN
00133       END

      END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS SCNTL
FOR S9A-07/27/72-17:43:50 (,0)

    SUBROUTINE SCNTL      ENTRY POINT 000147

    STORAGE USED: CODE(1) 000174; DATA(0) 000014; BLANK COMMON(2) 000000

     COMMON BLOCKS:

     0003   MCT    000005
     0004   VAB    000003
     0005   BLKI   000024

    EXTERNAL REFERENCES (BLOCK, NAME)

     0006   NWDU3
     0007   NI02$
     0010   NERR3$

    STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

     0000   000002 2000F     0001   000054 5L      0001   000061 50L     0001   000135 60L     0003 R 000000 DLMT
     0000 R 000000 DXSTR     0003 R 000003 DXWRT   0004 R 000002 ET     0003 I 000001 ICNT    0000   000006 INJP$
     0000 I 000001 LCNT      0003 I 000004 LSTEP   0005 R 000000 VAL    0003 R 000002 XWRT    0004 R 000000 Z1
     0004 R 000001 Z2


 00101            SUBROUTINE SCNTL(Y,DY,DX,X,NTRY,IFVD)
 00101         C
 00101         C  INTEGRATION CONTROL PROGRAM
 00101         C
 00103            DIMENSION Y(20),DY(20)
 00104            COMMON /MCT/ DLMT,ICNT,XWRT,DXWRT,LSTEP
 00104           1        /VAB/ Z1,Z2,ET
 00104           2        /BLKI/VAL(20)
 00105            ICNT    = ICNT+1
 00106            IF(DX.GE.DXWRT.AND.ICNT.GT.1) LSTEP = 1
 00110            IF(ABS(X-XWRT).LT.DLMT) GO TO 50
 00112            IF(XWRT.GT.X) GO TO 5
 00112         C
 00114            DXSTR   = DX
 00115            DX      = DX+XWRT-X
 00116            LCNT    = 1
 00117            NTRY    = 3
 00120            RETURN
 00120         C
 00121          5 NTRY    = 1
 00122            RETURN
 00122         C
 00123        50  WRITE(6,2000) Y(1),Y(2),Z1,Z2,ET,VAL(3),VAL(4),X
 00135      2000 FORMAT (8F15.7)
```

```
00136          IF(LCNT.EQ.1) DX = DXSTR
00140          LCNT    = 0
00141          IF(ABS(1.0-XWRT).LE.DLMT) GO TO 60
00143          XWRT    = XWRT+DXWRT
00144          NTRY    = 1
00145          IF(LSTEP.EQ.0) RETURN
00147          DX      = DXWRT
00150          IFVD    = 1
00151          RETURN
00151    C
00152       60 NTRY    = 2
00153          RETURN
00154          END

     END OF COMPILATION:       NO  DIAGNOSTICS.
```

```
@FOR,IS BNDCND
FOR S9A-07/27/72-17:43:54 (,0)

   SUBROUTINE BNDCND    ENTRY POINT 000350

   STORAGE USED: CODE(1) 000411; DATA(0) 000065; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003   BLKB   000002

   EXTERNAL REFERENCES (BLOCK, NAME)

    0004   FMINV
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000115 600L     0001   000130 601L     0001   000134 602L     0001   000137 603L     0001   000167 610L
    0001   000202 611L     0001   000206 612L     0001   000211 613L     0001   000241 620L     0001   000254 621L
    0001   000260 622L     0001   000263 623L     0001   000313 630L     0001   000040 700L     0000 R 000000 AN
    0003   000000 DNCBDU   0003   000001 DNCBDV   0000 I 000017 I       0000   000044 INJP$    0000 I 000020 J
    0000 I 000021 K        0000 R 000014 XN       0000 R 000022 Z1      0000 R 000023 Z2        0000 R 000024 Z3


 00101      1*          SUBROUTINE BNDCND(Y,U,V,FNCBR,XM)
 00101      2*     C
 00101      3*     C    BNDCND INSURES U,V, AND NCBAR ARE WITHIN THEIR BOUNDARY CONDITIONS
 00101      4*     C
 00103      5*          DIMENSION AN(3,4),XN(3),XM(3),Y(20)
 00104      6*          COMMON /BLKB/DNCBDU,DNCBDV
 00105      7*          I        = 0
 00106      8*          J        = 0
 00107      9*          K        = 0
 00110     10*          Z1       = U
 00111     11*          Z2       = V
 00112     12*          Z3       = FNCBR
 00113     13*          U        = Z1+XM(1)
 00114     14*          V        = Z2+XM(2)
 00115     15*          FNCBR    = Z3+XM(3)
 00116     16*          AN(1,1) =  Y(5)
 00117     17*          AN(1,2) =  Y(15)
 00120     18*          AN(1,3) =  Y(17)
 00121     19*          AN(2,1) =  Y(15)
 00122     20*          AN(2,2) =  Y(9)
 00123     21*          AN(2,3) =  Y(19)
 00124     22*          AN(3,1) = Y(17)
 00125     23*          AN(3,2) = Y(19)
 00126     24*          AN(3,3) = Y(13)
 00127     25*      700 IF (U.LT.4.00E-06.OR.U.GT.250.1) GO TO 600
 00131     26*          IF (V.LT.4.00E-05.OR.V.GT.50.01) GO TO 610
```

```
00133               IF (FNCBR.LT.0.00009.OR.FNCBR.GT.4.01) GO TO 620
00135               RETURN
00136         600   IF (U.LE.5.0E-06) GO TO 601
00140               IF (U.GE.250.) GO TO 602
00142               GO TO 610
00143         601   XN(1)    = 5.0E-06-Z1
00144               GO TO 603
00145         602   XN(1)    = 250.-Z1
00146         603   AN(1,1) = 1.
00147               AN(1,2) = 0.
00150               AN(1,3) = 0.
00151               I        = 1
00152               IF(I.EQ.0) XN(1) = -Y(3)
00154               IF(J.EQ.0) XN(2) = -Y(7)
00156               IF(K.EQ.0) XN(3) = -Y(11)
00160               CALL FMINV(AN,XN,3,4)
00161         610   IF (V.LE.5.0E-05) GO TO 611
00163               IF (V.GE.50.) GO TO 612
00165               GO TO 620
00166         611   XN(2)    = 5.0E-05-Z2
00167               GO TO 613
00170         612   XN(2)    = 50.-Z2
00171         613   AN(2,1) = 0.
00172               AN(2,2) = 1.
00173               AN(2,3) = 0.
00174               J        = 1
00175               IF(I.EQ.0) XN(1) = -Y(3)
00177               IF(J.EQ.0) XN(2) = -Y(7)
00201               IF(K.EQ.0) XN(3) = -Y(11)
00203               CALL FMINV(AN,XN,3,4)
00204         620   IF (FNCBR.LE.1.0E-04) GO TO 621
00206               IF (FNCBR.GE.4.00) GO TO 622
00210               GO TO 630
00211         621   XN(3)    = 1.0E-04-Z3
00212               GO TO 623
00213         622   XN(3)    = 4.00-Z3
00214         623   AN(3,1) = 0.
00215               AN(3,2) = 0.
00216               AN(3,3) = 1.
00217               K        = 1
00220               IF(I.EQ.0) XN(1) = -Y(3)
00222               IF(J.EQ.0) XN(2) = -Y(7)
00224               IF(K.EQ.0) XN(3) = -Y(11)
00226               CALL FMINV(AN,XN,3,4)
00227         630   XM(1)    = XN(1)
00230               XM(2)    = XN(2)
00231               XM(3)    = XN(3)
00232               U        = Z1+XM(1)
00233               V        = Z2+XM(2)
00234               FNCBR    = Z3+XM(3)
00235         660   GO TO 700
00236               END

      END OF COMPILATION:       NO DIAGNOSTICS.
```

```
2     @FOR,IS RESBND
      FOR S9A-07/27/72-17:44:04 (,0)

      SUBROUTINE RESBND     ENTRY POINT 000203

      STORAGE USED: CODE(1) 000232; DATA(0) 000053; BLANK COMMON(2) 000000

      EXTERNAL REFERENCES (BLOCK, NAME)

       0003    SQRT
       0004    NWDU$
       0005    NIO2$
       0006    NERR3$

      STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

       0001    000026 1L         0001    000126 2L        0000    000007 2000F     0001    000144 3L       0001    000161 4L
       0000 R 000003 A           0000 R 000004 B          0000 R 000005 C          0000 R 000006 EPS       0000    000037 INJP$
       0000 R 000000 U2          0000 R 000001 V2         0000 R 000002 Z

    00101        1*             SUBROUTINE RESBND(U,V,XM,ASTAR)
    00101        2*       C
    00101        3*       C     RESBND CHECKS THE BOUNDARY OF LAMBDA AND KEEPS ASTAR
    00101        4*       C     GREATER THAN U*V
    00101        5*       C
    00103        6*             DIMENSION XM(3)
    00104        7*             U2        = U-XM(1)
    00105        8*             V2        = V-XM(2)
    00106        9*             Z         = ASTAR-U*V
    00107       10*             IF(Z.LT.2.*U*V*1.0E-06) GO TO 1
    00111       11*             RETURN
    00111       12*       C
    00112       13*           1 A         = XM(1)*XM(2)
    00113       14*             B         = U2*XM(2)+V2*XM(1)
    00114       15*             C         = U2*V2-0.99*ASTAR
    00115       16*             IF(ABS(C).LE.1.0E-05.AND.XM(2).LT.0.) GO TO 2
    00117       17*             IF(ABS(C).LE.1.0E-05.AND.XM(1).LT.0.) GO TO 3
    00117       18*       C
    00121       19*             EPS       = (-B+SQRT(B**2.-4.*A*C))/2./A
    00122       20*             XM(1)     = EPS*XM(1)
    00123       21*             XM(2)     = EPS*XM(2)
    00124       22*             U         = U2+XM(1)
    00125       23*             V         = V2+XM(2)
    00126       24*             GO TO 4
    00127       25*           2 EPS       = (0.99*ASTAR-U2*V)/(V*XM(1))
    00130       26*             XM(1)     = EPS*XM(1)
    00131       27*             U         = U2+XM(1)
    00132       28*             GO TO 4
    00133       29*           3 EPS       = (0.99*ASTAR-U*V2)/(U*XM(2))
    00134       30*             XM(2)     = EPS*XM(2)
```

```
00135                 V       = V2+XM(2)
00135           C
00136             4  WRITE(6,2000) XM(1),XM(2),EPS
00143          2000 FORMAT (//5X'EPSILON CALCULATED        DELTAU ='E14.6/
00143             1          31X'    DELTAV ='E14.6/31X'EPSILON =     'E14.6)
00143           C
00144                 RETURN
00145                 END

        END OF COMPILATION:          NO  DIAGNOSTICS.
```

158669

```
@FOR,IS REST
FOR S9A-07/27/72-17:44:10 (,0)

SUBROUTINE REST      ENTRY POINT 000066

STORAGE USED: CODE(1) 000120; DATA(0) 000023; BLANK COMMON(2) 000000

EXTERNAL REFERENCES (BLOCK, NAME)

 0003    NERR3$

STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

 0000 R 000000 A1         0000   000003 INJP$


00101           SUBROUTINE REST(U,V,ASTAR,RLAM,DLDU,DLDV,D2LDUU,D2LDUV,D2LDVV,
00101          1DLDNCB,D2LNCB,D2LUNB,D2LVNB)
00101     C
00101     C     CONSTANT AREA RESTRAINT
00101     C
00103           A1      = ASTAR-U*V
00104           RLAM    = 2*U*V/A1
00105           DLDU    = 2.*ASTAR*V/A1**2.
00106           DLDV    = 2.*ASTAR*U/A1**2.
00107           D2LDUU  = 4.*ASTAR*V**2./A1**3.
00110           D2LDUV  = 2.*ASTAR*(ASTAR+U*V)/A1**3.
00111           D2LDVV  = 4.*ASTAR*U**2./A1**3.
00112           DLDNCB  = 0.
00113           D2LNCB  = 0.
00114           D2LUNB  = 0.
00115           D2LVNB  = 0.
00116           RETURN
00117           END

     END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS NDERV
FOR S9A-07/27/72-17:44:13 (,0)

   SUBROUTINE NDERV     ENTRY POINT 000056

   STORAGE USED: CODE(1) 000070; DATA(0) 000015; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   SQRT
    0004   ASIN
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000000 C4       0000 R 000001 C5       0000 R 000002 C6       0000    000006 INJP$


 00101      1*           SUBROUTINE NDERV(RLAM,FN,DFNX,D2NDLL)
 00101      2*      C
 00101      3*      C    N AND ITS DERIVATIVES
 00101      4*      C
 00103      5*           C4      = RLAM+1.0
 00104      6*           C5      = RLAM+2.0
 00105      7*           C6      = SQRT(RLAM*C5)
 00106      8*           FN      = (1.5707963+C5-C6-ASIN(1.0/C4))/RLAM
 00107      9*           DFNX    = -(FN+C6/C4-1.0)/RLAM
 00110     10*           D2NDLL  = -(2.0*DFNX+1.0/(C4*C4*C6))/RLAM
 00111     11*           RETURN
 00112     12*           END

       END OF COMPILATION:        NO  DIAGNOSTICS.
```

158671

```
@FOR,IS MDER
FOR S9A-07/27/72-17:44:16 (,0)

      SUBROUTINE MDER      ENTRY POINT 000251

      STORAGE USED: CODE(1) 000304; DATA(0) 000066; BLANK COMMON(2) 000000

      EXTERNAL REFERENCES (BLOCK, NAME)

        0003   SQRT
        0004   ASIN
        0005   NERR3$

      STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

        0000 R 000011 CFN      0000 R 000000 C1       0000 R 000017 C10      0000 R 000020 C11      0000 R 000022 C12
        0000 R 000001 C2       0000 R 000003 C3       0000 R 000002 C4       0000 R 000004 C5       0000 R 000005 C6
        0000 R 000006 C7       0000 R 000007 C8       0000 R 000010 C9       0000 R 000015 DCFDNC   0000 R 000013 DCFNDL
        0000 R 000014 DFFSDL   0000 R 000016 D2CFLL   0000 R 000025 D2CFNC   0000 R 000026 D2CLNC   0000 R 000023 D2C2LL
        0000 R 000021 D2C3LL   0000 R 000024 D2FSLL   0000 R 000027 D3C2LN   0000 R 000030 D3C2NL   0000 R 000012 FFS
        0000   000040 INJP$

   00101      1*             SUBROUTINE MDER(RLAM,FNC,FM,DFMX,DFM,D2FMLL,D2MDNC,D2MLNC,D3M2LN,
   00101      2*            1 D3M2NL)
   00101      3*       C
   00101      4*       C       AND ITS DERIVATIVES
   00101      5*       C
   00103      6*             C1       = 0.1460*FNC-0.02866
   00104      7*             C2       = SQRT(RLAM*(2.+RLAM))
   00105      8*             C4       = 1.0/(RLAM+1.0)
   00106      9*             C3       = ASIN(C4)
   00107     10*             C5       = 1/(C4*C2)
   00110     11*             C6       = (C4**2)/SQRT(1-C4**2)
   00111     12*             C7       = 1/(RLAM**2)
   00112     13*             C8       = FNC/RLAM
   00113     14*             C9       = 2.*C7*C8
   00114     15*             CFN      = 1.0-C1*C8
   00115     16*             FFS      = (C2+C3-1.57079635)/RLAM
   00116     17*             FM       = CFN*FFS
   00117     18*             DCFNDL   = C1*C7*FNC
   00120     19*             DFFSDL   = (C5-C6-FFS)/RLAM
   00121     20*             DFMX     = CFN*DFFSDL+FFS*DCFNDL
   00122     21*             DCFDNC   = -(0.1460*FNC+C1)/RLAM
   00123     22*             DFM      = FFS*DCFDNC
   00124     23*             D2CFLL   = -C1*C9
   00125     24*             C10      = 1-C4**2
   00126     25*             C11      = +1.+0.5/C10*C4**2
   00127     26*             D2C3LL   = 2*(C4**3)*C11/SQRT(C10)
   00130     27*             C12      = 1/C2-C2*(C4**2)
   00131     28*             D2C2LL   = -C12/(C4*C2)**2
```

```
      D2FSLL  = (D2C2LL+D2C3LL-2.*DFFSDL)/RLAM
      D2FMLL  = CFN*D2FSLL+2.*DFFSDL*DCFNDL+FFS*D2CFLL
      D2CFNC  = -0.2920/RLAM
      D2MDNC  = FFS*D2CFNC
      D2CLNC  = (0.146*FNC+C1)*C7
      D2MLNC  = DCFDNC*DFFSDL+D2CLNC*FFS
      D3C2LN  = -2.*D2CLNC/RLAM
      D3M2LN  = DCFDNC*D2FSLL+2.*DFFSDL*D2CLNC+FFS*D3C2LN
      D3C2NL  = 0.2920*C7
      D3M2NL  = FFS*D3C2NL+DFFSDL*D2CFNC
      RETURN
      END

 END OF COMPILATION:        NO  DIAGNOSTICS.
```

1586721

```
@FOR,IS NCDERV
FOR S9A-07/27/72-17:44:19 (,0)

     SUBROUTINE NCDERV     ENTRY POINT 000031

     STORAGE USED: CODE(1) 000044; DATA(0) 000013; BLANK COMMON(2) 000000

     EXTERNAL REFERENCES (BLOCK, NAME)

      0003    NERR3$

     STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

      0000   C00004 INJP$      0000 R 000000 T2         0000 R 000001 T3


   00101       1*             SUBROUTINE NCDERV(FNCBR,THETAB,FNC,DNCDT1,D2CD2T,D2CTNB)
   00101       2*      C
   00101       3*      C      NC AND ITS DERIVATIVES
   00101       4*      C
   00103       5*             T2       = THETAB**2
   00104       6*             T3       = T2*THETAB
   00105       7*             FNC      = FNCBR*T3
   00106       8*             DNCDT1   = 3.*FNCBR*T2
   00107       9*             D2CD2T   = 6.*FNCBR*THETAB
   00110      10*             D2CTNB   = 3.*T2
   00111      11*             RETURN
   00112      12*             END

        END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS MIXDER
FOR S9A-07/27/72-17:44:49 (,0)

SUBROUTINE MIXDER      ENTRY POINT 000347

STORAGE USED: CODE(1) 000454; DATA(0) 000104; BLANK COMMON(2) 000000

 COMMON BLOCKS:

 0003   BLKI    000024
 0004   BLKD    000012

EXTERNAL REFERENCES (BLOCK, NAME)

 0005   DDETA
 0006   DETA
 0007   DDDETA
 0010   ETA
 0011   NERR3$

STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

 0004 R 000003 A1        0004 R 000004 A2        0004 R 000005 A3        0004 R 000006 A4        0004 R 000007 A5
 0004 R 000010 A6        0007 R 000000 DDDETA    0005 R 000000 DDETA     0006 R 000000 DETA      0003   000023 DE1DL
 0003   000021 DE4DT     0003 R 000013 DFM       0003 R 000012 DFMX      0003 R 000010 DFNX      0003   000007 DNCDT1
 0000 R 000006 DNCDX     0000 R 000003 D2A1XY    0000 R 000020 D2A2XY    0000 R 000021 D2A3XY    0000 R 000022 D2A4XY
 0000 R 000015 D2A5X     0000 R 000004 D2A6XY    0000 R 000017 D2EBXY    0000 R 000012 D2EPXY    0000 R 000011 D2EXY
 0003 R 000016 D2FML     0000 R 000013 D2MDLY    0003 R 000015 D2MONC    0000 R 000014 D2MDXY    0003 R 000014 D2MLNC
 0003 R 000011 D2NDL     0000 R 000016 D2NDXY    0000 R 000007 D3MNLY    0000 R 000010 D3MNXY    0004 R 000001 D3M2LN
 0004 R 000002 D3M2N     0000 R 000005 D3M2NY    0004 R 000011 EB        0010 R 000000 ETA       0003   000022 E3
 0003 R 000002 FM        0003   000003 FN        0003 R 000005 FNC       0003 R 000004 FNCBR     0000   000026 INJP$
 0003   000000 THETA     0003   000001 THETAS    0004 R 000000 U         0003   000006 V         0000 R 000000 Y
 0003   000017 Y1        0003 R 000020 Y2        0000 R 000002 Z
```

```
00101           SUBROUTINE MIXDER(DTBDX,DTBDY,DTFDY,D2TBXY,D2TFXY,DNCDX,DNCDY,
00101          1                     D2TBYE,DA1DX,DA1DY,DA2DX,DA2DY,DA3DX,DA3DY,
00101          2                     DA4DY,DA5DX,DA5DY,DA6DX,DA6DY,DLDX,DLDY,
00101          3                     D2LDXY,DEBDY,DEBDX,DEX,DEY,DEPX,DEPY,DMDX,
00101          4                     DMDY,D2MNCX,D2MNCY,B,C,D3TXYE,DTFDXY)
00101    C
00101    C      FOR MIXED DERIVATIVES OF U AND V      SET B=1. AND C= 0.
00101    C      FOR MIXED DERIVATIVES OF U AND FNCBR SET B=1. AND C= 1.
00101    C      FOR MIXED DERIVATIVES OF V AND FNCBR SET B=0. AND C= 1.
00101    C
00103           DIMENSION Y(2)
00104           COMMON /BLKI/THETAB,THETAS,FM,FN,FNCBR,FNC,V,DNCDT1,DFNX,D2NDLL,
00104          1          DFMX,DFM,D2MLNC,D2MONC,D2FMLL,Y1,Y2,DE4DTB,E3,DE1DL/
00104          2     BLKD/U,D3M2LN,D3M2NL,A1,A2,A3,A4,A5,A6,EB
00105           Y(2)     = Y2
00106           Z        = FNC
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00107      DTFDXY  = U*(D2TBXY-D2TFXY)+B*(DTBDY-DTFDY)
00110      D2A1XY  = 2*DA1DX*DA1DY/A1-A1**2*(D2TFXY-D2TBXY)
00111      D2A6XY  = 6*FNCBR*DTBDX*DTBDY+6*Y(2)*FNCBR*D2TBXY+C*6*Y(2)*DTBDX
00112      D3M2NY  = DLDY*D3M2NL
00113      DNCDXY  = 6*FNCBR*Y(2)*DTBDX*DTBDY+3*FNCBR*(Y(2)**2)*D2TBXY+
00113     1          C*3*(Y(2)**2)*DTBDX
00114      D3MNLY  = DLDY+D3M2LN+DNCDY*D3M2NL
00115      D3MNXY  = D3MNLY*DLDX+D2MLNC*D2LDXY+D3M2NY*DNCDX+D2MDNC*DNCDXY
00116      D2EXY   = DDETA(Z)*DNCDX*DNCDY+DETA(Z)*DNCDXY
00117      D2EPXY  = DDDETA(Z)*DNCDX*DNCDY+DDETA(Z)*DNCDXY
00120      D2MDLY  = DLDY*D2FMLL+DNCDY*D2MLNC
00121      D2MDXY  = DLDX*D2MDLY+DFMX*D2LDXY+D2MNCY*DNCDX+DFM*DNCDXY
00122      D2A5XY  = FM*D2EPXY+DEPX*DMDY+DEPY*DMDX+DETA(Z)*D2MDXY+DEY*D2MNCX+
00122     1          ETA(Z)*D3MNXY+DEX*D2MNCY+DFM*D2EXY
00123      D2NDXY  = DFNX+D2LDYY+DLDX*DLDY+D2NDLL
00124      D2EBXY  = FM*D2EXY+DMDY*DEX+ETA(Z)*D2MDXY+DEY*DMDX+D2NDXY
00125      D2A2XY  = -(DEBDY*DA2DX+DEBDX*DA2DY+A2*D2EBXY-(A6*D2A5XY+
00125     1          DA6DY*DA5DX+DA5DY*DA6DX+A5*D2A6XY))/EB
00126      D2A3XY  = DA3DX*DA3DY/A3+D2TBXY*DA3DX/DTBDX+
00126     1          A3*DTBDX*(-3*DTBDY/Y(2)**2-DA3DY)
00127      D2A4XY  = D2A1XY+D2A2XY+D2A3XY
00130      D3TXYE  = U*D2A4XY/A4**2-DA4DY*(2*A4*D2TBXE+B)/A4**2
00131      RETURN
00132      END

      END OF COMPILATION:        NO DIAGNOSTICS.
```

```
@FOR,IS DERV
FOR S9A-07/27/72-17:44:54 (,0)

SUBROUTINE DERV        ENTRY POINT 000604

STORAGE USED: CODE(1) 000721; DATA(0) 000130; BLANK COMMON(2) 000000

COMMON BLOCKS:

0003   BLKI    000024
0004   BLKD    000012

EXTERNAL REFERENCES (BLOCK, NAME)

0005   ETA
0006   DETA
0007   DDETA
0010   DDDETA
0011   NERR3$

STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

0004 R 000003 A1        0004 R 000004 A2        0004 R 000005 A3        0004 R 000006 A4        0004 R 000007 A5
0004 R 000010 A6        0000 R 000051 A7        0000 R 000063 DA7DU     0010 R 000000 DDDETA    0007 R 000000 DDETA
0006 R 000000 DETA      0003   000023 DE1DL     0003   000021 DE4DTB    0003 R 000013 DFM       0003 R 000012 DFMX
0003 R 000010 DFNX      0003   000007 DNCDT1    0000 R 000052 DNDU      0000 R 000024 DY        0000 R 000053 D2A1UU
0000 R 000066 D2A2UU    0000 R 000067 D2A3UU    0000 R 000070 D2A4UU    0000 R 000061 D2A5UU    0000 R 000062 D2A6U
0000 R 000065 D2EBUU    0000 R 000055 D2EPUU    0000 R 000060 D2EUU     0003 R 000016 D2FMLL    0003 R 000015 D2MDNC
0003 R 000014 D2MLNC    0000 R 000056 D2MUU     0000 R 000054 D2NCUU    0003 R 000011 D2NDLL    0000 R 000064 D2NUU
0000 R 000057 D3MNUU    0004 R 000001 D3M2LN    0004 R 000002 D3M2NL    0004 R 000011 EB        0005 R 000000 ETA
0003   000022 E3        0003 R 000002 FM        0003 R 000003 FN        0003 R 000005 FNC       0003 R 000004 FNCBR
0000   000077 INJP$     0003   000000 THETAB    0003 R 000001 THETAS    0004 R 000000 U         0003   000006 V
0000 R 000000 Y         0003 R 000017 Y1        0003 R 000020 Y2        0000 R 000050 Z


00101      1*                 SUBROUTINE DERV(Y3,Y4,Y5,Y6,DLDU,D2LDUU,DY3,DY4,DY5,DY6,B,C,
00101      2*            1              DNCDU,DA1DU,DA2DU,DA3DU,DA4DU,DA5DU,DA6DU,
00101      3*            2              DEPDU,DEU,DEPU,DMDU,D2MNCU)
00101      4*          C
00101      5*          C      DERIVATIVES
00101      6*          C
00101      7*          C      FOR FIRST AND SECOND DERIVATIVES OF     U SET C=1 AND B=0
00101      8*          C      FOR FIRST AND SECOND DERIVATIVES OF     V SET C=0 AND B=0
00101      9*          C      FOR FIRST AND SECOND DERIVATIVES OF FNCBR SET C=0 AND B=1
00101     10*          C
00103     11*                 DIMENSION Y(20),DY(20)
00104     12*                 COMMON /BLKI/THETAB,THETAS,FM,FN,FNCBR,FNC,V,DNCDT1,DFNX,D2NDLL,
00104     13*            1             DFMX,DFM,D2MLNC,D2MDNC,D2FMLL,Y1,Y2,DE4DTB,E3,DE1DL/
00104     14*            2       BLKD/U,D3M2LN,D3M2NL,A1,A2,A3,A4,A5,A6,EB
00105     15*                 Y(1)     = Y1
00106     16*                 Y(2)     = Y2
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      Y(3)    = Y3
      Y(4)    = Y4
      Y(5)    = Y5
      Y(6)    = Y6
      Z       = FNC
      EB      = FM*ETA(Z)+FN
      A1      = 1./(Y(1)-Y(2))
      A5      = FM*DETA(Z)+ETA(Z)*DFM
      A6      =-3*Y(2)**2*FNCBR
      A2      = A6*A5/EB
      A3      = 4*Y(2)**3/(Y(2)**4-THETAS**4)
      A4      = A1+A2+A3
      DA1DU   = -A1**2*(Y(3)-Y(4))
      DNCDU   = A6*Y(4)+B*Y(2)**3
      DEPU    = DDETA(Z)*DNCDU
      DMDU    = DFMX*DLDU+DFM*DNCDU
      D2MNCU  = D2MLNC*DLDU+D2MDNC*DNCDU
      DEU     = DETA(Z)*DNCDU
      DA5DU   = FM*DEPU+DETA(Z)*DMDU+ETA(Z)*D2MNCU+DFM*DEU
      DA6DU   = 6*Y(2)*FNCBR*Y(4)+B*3*Y(2)**2
      A7      = A6*DA5DU+A5*DA6DU
      DNDU    = DFNX*DLDU
      DEBDU   = FM*DEU+ETA(Z)*DMDU+DNDU
      DA2DU   = (A7-A2*DEBDU)/EB
      DA3DU   = A3*Y(4)*(3/Y(2)-A3)
      DA4DU   = DA1DU+DA2DU+DA3DU
      DY(4)   = -C/A4+U/A4**2*DA4DU
      D2A1UU  = -A1**2*(Y(5)-Y(6))-2*A1*DA1DU*(Y(3)-Y(4))
      D2NCUU  = A6*Y(5)+DA6DU*Y(4)+B*3*Y(4)*Y(2)**2
      D2EPUU  = DDETA(Z)*D2NCUU+DNCDU**2*DDDETA(Z)
      D2MUU   = DFMX*D2LDUU+DLDU*(D2FMLL*DLDU+D2MLNC*DNCDU)+DFM*D2NCUU
     1          +DNCDU*(D2MLNC*DLDU+D2MDNC*DNCDU)
      D3MNUU  = D2MLNC*D2LDUU+DLDU*(D3M2LN*DLDU+D3M2NL*DNCDU)
     1          +D2MDNC*D2NCUU+DNCDU*D3M2NL*DLDU
      D2EUU   = DETA(Z)*D2NCUU+DDETA(Z)*DNCDU**2
      D2A5UU  = FM*D2EPUU+2*DEPU*DMDU+DETA(Z)*D2MUU+ETA(Z)*D3MNUU
     1          +2*DEU*D2MNCU+DFM*D2EUU
      D2A6U   = 6*Y(2)*FNCBR*Y(6)+6*FNCBR*Y(4)**2+B*12*Y(2)*Y(4)
      DA7DU   = A6*D2A5UU+DA5DU*DA6DU+A5*D2A6U+DA6DU*DA5DU
      D2NUU   = DFNX*D2LDUU+D2NDLL*DLDU**2
      D2EBUU  = FM*D2EUU+2*DEU*DMDU+ETA(Z)*D2MUU+D2NUU
      D2A2UU  = (DA7DU-A2*D2EBUU-2*DEBDU*DA2DU)/EB
      D2A3UU  = A3*((3/Y(2)-A3)*Y(6)+Y(4)*(-3/Y(2)**2*Y(4)-DA3DU)
     1          +(1/A3*DA3DU)**2)
      D2A4UU  = D2A1UU+D2A2UU+D2A3UU
      DY(6)   = -2/A4*DY(4)*DA4DU+U/A4**2*D2A4UU
      DY(3)   = U*(Y(4)-Y(3))+(Y(2)-Y(1))*C
      DY(5)   = U*(Y(6)-Y(5))+2*(Y(4)-Y(3))*C
      DY3     = DY(3)
      DY4     = DY(4)
      DY5     = DY(5)
      DY6     = DY(6)
      RETURN
      END

END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS INTIAL
FOR S9A-07/27/72-17:44:59 (,0)

SUBROUTINE INTIAL      ENTRY POINT 000470

STORAGE USED: CODE(1) 000522; DATA(0) 000123; BLANK COMMON(2) 000000

COMMON BLOCKS:

0003   BLKI   000024

EXTERNAL REFERENCES (BLOCK, NAME)

0004   ETA
0005   DETA
0006   DDETA
0007   NERR3$

STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

0000 R 000037 A1      0000 R 000040 A2      0000 R 000041 A3      0000 R 000053 B1      0000 R 000054 B2
0006 R 000000 DDETA   0000 R 000051 DDETDU  0005 R 000000 DETA    0000 R 000046 DETADU  0003 R 000023 DE1DL
0000 R 000032 DE1DN   0000 R 000027 DE1DTB  0000 R 000047 DE1DU   0000 R 000030 DE2DTB  0000 R 000034 DE2DU
0000 R 000031 DE3DT   0000 R 000035 DE3DU   0003 R 000021 DE4DTB  0000 R 000033 DE4DU   0000 R 000044 DECNDU
0003 R 000013 DFM     0000 R 000045 DFMDU   0003 R 000012 DFMX    0000 R 000043 DFNDU   0003 R 000010 DFNX
0003 R 000007 DNCDT   0000 R 000061 D1      0000 R 000062 D2      0000 R 000065 D2E1CB  0000 R 000060 D2E1LU
0000 R 000055 D2E1T   0000 R 000036 D2E2TU  0000 R 000042 D2E3TU  0000 R 000066 D2E4CB  0000 R 000071 D2E4UU
0003 R 000016 D2FML   0000 R 000056 D2MDLU  0003 R 000015 D2MDNC  0003 R 000014 D2MLNC  0000 R 000052 D2MNCU
0000 R 000067 D2NCN   0000 R 000050 D2NCTU  0003 R 000011 D2NDLL  0000 R 000057 D2NDLU  0000 R 000063 D3
0000 R 000064 D4      0004 R 000000 ETA     0000 R 000025 E1      0000 R 000026 E2      0003 R 000022 E3
0003 R 000002 FM      0003 R 000003 FN      0003 R 000005 FNC     0003 R 000004 FNCBR   0000   000100 INJP$
0000 R 000070 TERMN   0003 R 000000 THETAB  0003 R 000001 THETAS  0003 R 000006 V       0000 R 000000 Y
0003 R 000017 Y1      0003 R 000020 Y2      0000 R 000024 Z


00101        SUBROUTINE INTIAL(DLDU,D2LDUU,Y3,Y4,Y5,Y6,B,C,D2E4TU,D2E4LU)
00101   C
00101   C    INTIAL CONDITIONS
00101   C
00101   C    FOR FIRST AND SECOND DERIVATIVES OF     U SET C=1 AND B=0
00101   C    FOR FIRST AND SECOND DERIVATIVES OF     V SET C=0 AND B=0
00101   C    FOR FIRST AND SECOND DERIVATIVES OF FNCBR SET C=1 AND B=1
00101   C
00103        DIMENSION Y(20)
00104        COMMON /BLKI/THETAB,THETAS,FM,FN,FNCBR,FNC,V,DNCDT1,DFNX,D2NDLL,
00104       1               DFMX,DFM,D2MLNC,D2MDNC,D2FMLL,Y1,Y2,DE4DTB,E3,DE1DL
00105        Y(1)    = Y1
00106        Y(2)    = Y2
00107        Z       = FNC
00110        E1      = FM*ETA(Z)+FN
00111        E2      = THETAB**4-THETAS**4
```

```
      E3     = E2/(1-THETAB)
      Y(3)   = 0.
      DE1DTB = DNCOT1*(DFM*ETA(Z)+FM*DETA(Z))
      DE2DTB = 4.*(THETAB**3)
      DE3DTB = E3*(DE2DTB+E3)/E2
      DE4DTB = E1*DE3DTB+E3*DE1DTB
      DE1DL  = ETA(Z)*DFMX+DFNX
      DE1DNC = ETA(Z)*DFM+DETA(Z)*FM
      DE4DU  = E3*DE1DL*DLDU+B*E3*DE1DNC*THETAB**3
      Y(4)   = -((1-C)/V**2+DE4DU)/DE4DTB
      Y(5)   = 0.
      DE2DU  = DE2DTB*Y(4)
      DE3DU  = E3*(E3*Y(4)+DE2DU)/E2
      D2E2TU = 12.*Y(4)*(THETAB**2)
      A1     = E3*(D2E2TU+DE3DU)/E2
      A2     = DE2DTB+E3
      A3     = -E3*DE2DU/(E2**2)+DE3DU/E2
      D2E3TU = A1+A2*A3
      DFNDU  = DFNX*DLDU
      DFCNDU = DNCOT1*Y(4)+B*Y(2)**3
      DFMDU  = DFMX*DLDU+DFM*DFCNDU
      DETADU = DETA(Z)*DFCNDU
      DE1DU  = FM*DETADU+ETA(Z)*DFMDU+DFNDU
      D2NCTU = 6*ENCBR*Y(2)*Y(4)+B*3*Y(2)**2
      DDETDU = DDETA(Z)*DFCNDU
      D2MNCU = D2MLNC*DLDU+D2MDNC*DFCNDU
      B1     = DFM*DETADU+ETA(Z)*D2MNCU+FM*DDETDU+DETA(Z)*DFMDU
      B2     = DE1DTB*D2NCTU/DNCOT1
      D2E1TU = DNCOT1*B1+B2
      D2MDLU = D2FMLL*DLDU+D2MLNC*DFCNDU
      D2NDLU = D2NDLL*DLDU
      D2E1LU = ETA(Z)*D2MDLU+DETADU*DFMX+D2NDLU
      D2E4LU = E3*D2E1LU+DE1DL*DE3DU
      D1     = DETA(Z)*DFCNDU*DFM
      D2     = ETA(Z)*D2MNCU
      D3     = DDETA(Z)*FM*DFCNDU
      D4     = DETA(Z)*DFMDU
      D2E1CB = D1+D2+D3+D4
      D2E4CB = DE3DU*DE1DNC+E3*D2E1CB
      D2NCNB = 3*Y(4)*Y(2)**2
      TERMNB = B*(E3*DE1DNC*D2NCNB+Y(2)**3*D2E4CB)
      D2E4UU = E3*DE1DL*D2LDUU+DLDU*D2E4LU+TERMNB
      D2E4TU = E1*D2E3TU+DE3DTB*DE1DU+E3*D2E1TU+DE1DTB*DE3DU
      Y(6)   = -(Y(4)*D2E4TU+D2E4UU+2*(C-1)/V**3)/DE4DTB
      Y3     = Y(3)
      Y4     = Y(4)
      Y5     = Y(5)
      Y6     = Y(6)
      RETURN
      END

END OF COMPILATION:        NO DIAGNOSTICS.
```

```
@FOR,IS INTMIX
FOR S9A-07/27/72-17:45:03 (,0)

     SUBROUTINE INTMIX     ENTRY POINT 000024

     STORAGE USED: CODE(1) 000032; DATA(0) 000007; BLANK COMMON(2) 000000

      COMMON BLOCKS:

      0003   BLKI    000024

     EXTERNAL REFERENCES (BLOCK, NAME)

      0004   NERR3$

     STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

      0003 R 000023 DE1DL      0000 R 000000 DE4DL      0003 R 000021 DE4DTB     0000 R 000001 DE4DXY     0003   000013 DFM
      0003   000012 DFMX       0003   000010 DFNX       0003   000007 DNCDT1     0003   000016 D2FMLL     0003   000015 D2MDNC
      0003   000014 D2MLNC     0003   000011 D2NDLL     0003 R 000022 E3         0003   000002 FM         0003   000003 FN
      0003   000005 FNC        0003   000004 FNCBR      0000   000002 INJP$      0003   000000 THETAB     0003   000001 THETAS
      0003   000006 V          0003   000017 Y1         0003   000020 Y2


 00101       1*            SUBROUTINE INTMIX(D2E4TY,DTBDX,DLDX,D2E4LY,D2LDXY,D2TBXY,D2TFXY)
 00101       2*      C
 00101       3*      C     INITIAL MIXED DERIVATIVES
 00101       4*      C
 00103       5*            COMMON /BLKI/THETAB,THETAS,FM,FN,FNCBR,FNC,V,DNCDT1,DFNX,D2NDLL,
 00103       6*           1      DFMX,DFM,D2MLNC,D2MDNC,D2FMLL,Y1,Y2,DE4DTB,E3,DE1DL
 00104       7*            D2TFXY  = 0.
 00105       8*            DE4DL   = E3*DE1DL
 00106       9*            DE4DXY  = D2E4LY+DLDX+DE4DL*D2LDXY
 00107      10*            D2TBXY  = -(DE4DXY+DTBDX*D2E4TY)/DE4DTB
 00110      11*            RETURN
 00111      12*            END

        END OF COMPILATION:       NO  DIAGNOSTICS.
```


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```
@FOR,IS FMINV
FOR S9A-07/27/72-17:45:07 (,0)

    SUBROUTINE FMINV     ENTRY POINT 000254

    STORAGE USED: CODE(1) 000306; DATA(0) 001260; BLANK COMMON(2) 000000

    EXTERNAL REFERENCES (BLOCK, NAME)

     0003   NERR3$

    STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

     0001   000046 105G     0001   000151 11L      0001   000051 111G     0001   000071 117G     0001   000104 123G
     0001   000125 133G     0001   000130 137G     0001   000172 150G     0001   000175 154G     0001   000227 164G
     0001   000212 20L      0000 R 001214 AA       0000 R 001217 B       0000 I 001212 I       0000   001224 INJP$
     0000 I 001215 I1       0000 I 001220 I2       0000 I 001213 J       0000 I 001216 K       0000 R 000000 XMAT


 00101      1*           SUBROUTINE FMINV (A,X,N,M)                                  1
 00101      2*      C
 00101      3*      C    MATRIX INVERSION AND SOLUTION OF SIMULTANEOUS EQUATIONS
 00101      4*      C
 00103      5*           DIMENSION A(N,N),X(N),XMAT(25,26)                           2
 00104      6*           DO 1 I=1,N                                                  3
 00107      7*           XMAT(I,M) = X(I)                                            4
 00110      8*           DO 1 J=1,N                                                  5
 00113      9*         1 XMAT(I,J) = A(I,J)                                          6
 00116     10*           DO 20 I=1,N                                                 7
 00121     11*           AA = XMAT(I,I)                                              8
 00122     12*           DO 5 J=1,M                                                  9
 00125     13*         5 XMAT(I,J) = XMAT(I,J)/AA                                   10
 00127     14*           IF (I.EQ.1) GO TO 11                                       11
 00131     15*           I1 = I-1                                                   12
 00132     16*           DO 10 K=1,I1                                               13
 00135     17*           B = XMAT(K,I)                                              14
 00136     18*           DO 10 J=1,M                                                15
 00141     19*        10 XMAT(K,J) = XMAT(K,J) - XMAT(I,J) * B                      16
 00144     20*           IF (I.EQ.N) GO TO 20                                       17
 00146     21*        11 I2 = I+1                                                   18
 00147     22*           DO 15 K=I2,N                                                1
 00152     23*           B = XMAT(K,I)                                              20
 00153     24*           DO 15 J=1,M                                                21
 00156     25*        15 XMAT(K,J) = XMAT(K,J) - XMAT(I,J) * B                      22
 00161     26*        20 CONTINUE                                                   23
 00163     27*           DO 25 I=1,N                                                24
 00166     28*        25 X(I) = XMAT(I,M)                                           25
 00170     29*           RETURN                                                     26
 00171     30*           END

      END OF COMPILATION:          NO  DIAGNOSTICS.
```

```
@FOR,IS ETA
FOR S9A-07/27/72-17:45:11 (,0)

     FUNCTION ETA          ENTRY POINT 000036

     STORAGE USED: CODE(1) 000044; DATA(0) 000022; BLANK COMMON(2) 000000

     EXTERNAL REFERENCES (BLOCK, NAME)

      0003    POLY
      0004    EXP
      0005    NERR3$

     STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

      0001    000016 1L         0000 R 000001 A          0000 R 000010 B          0000 R 000000 ETA        0000    000014 INJP$
      0003 R 000000 POLY

00101       1*              FUNCTION ETA(X)
00101       2*        C
00101       3*        C     FIN EFFECTIVENESS OF THE UNOBSTRUCTED FIN
00101       4*        C
00103       5*              DIMENSION A(7), B(2)
00104       6*              DATA A(1),A(2),A(3),A(4),A(5),A(6),A(7)/0.10E+01, -0.1163143E+01,
00104       7*             1     0.1478836E+01, -0.1267550E+01, 0.6325223E+00, -0.1627067E+00,
00104       8*             2     0.1654223E-01/ B(1),B(2)/0.6866095E+00, -0.2297718E+00/
00116       9*              IF(X.GT.2.5) GO TO 1
00120      10*              ETA    = POLY(7,A,X)
00121      11*              RETURN
00122      12*            1 ETA    = B(1)*EXP(B(2)*X)
00123      13*              RETURN
00124      14*              END

         END OF COMPILATION:       NO  DIAGNOSTICS.
```

158683

```
@FOR,IS DETA
FOR S9A-07/27/72-17:45:15 (,0)

   FUNCTION DETA          ENTRY POINT 000036

   STORAGE USED: CODE(1) 000044; DATA(0) 000021; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003    POLY
    0004    EXP
    0005    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000016 1L         0000 R 000001 A          0000 R 000007 B          0000 R 000000 DETA       0000    000013 INJP$
    0003 R 000000 POLY


 00101       1*              FUNCTION DETA(X)
 00101       2*        C
 00101       3*        C     DETA/DNC
 00101       4*        C
 00103       5*              DIMENSION A(6), B(2)
 00104       6*              DATA A(1),A(2),A(3),A(4),A(5),A(6)/-0.1163143E+01, 0.2957672E+01,
 00104       7*             1     -0.3802650E+01, 0.2530089E+01, -0.8135335E+00, 0.9925338E-01/
 00104       8*             2     B(1),B(2)/-0.1577635E+00, -0.2297718E+00/
 00115       9*              IF(X.GT.2.5) GO TO 1
 00117      10*              DETA  = POLY(6,A,X)
 00120      11*              RETURN
 00121      12*            1 DETA  = B(1)*EXP(B(2)*X)
 00122      13*              RETURN
 00123      14*              END

        END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS DDETA
FOR S9A-07/27/72-17:45:23 (,0)

     FUNCTION DDETA       ENTRY POINT 000036

     STORAGE USED: CODE(1) 000044; DATA(0) 000020; BLANK COMMON(2) 000000

     EXTERNAL REFERENCES (BLOCK, NAME)

      0003    POLY
      0004    EXP
      0005    NERR3$

     STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

      0001   000016 1L        0000 R 000001 A        0000 R 000006 B        0000 R 000000 DDETA      0000    000012 INJP$
      0003 R 000000 POLY


 00101       1*             FUNCTION  DDETA(X)
 00101       2*       C
 00101       3*       C     D2ETA/D2NC
 00101       4*       C
 00103       5*             DIMENSION  A(5), B(2)
 00104       6*             DATA  A(1),A(2),A(3),A(4),A(5)/0.2957672E+01, -0.7605300E+01,
 00104       7*            1      0.7590267E+01, -0.3254134E+01, 0.4962669E+00/ B(1),B(2)/
 00104       8*            2      0.3624960E-01, -0.2297718E+00/
 00114       9*             IF(X.GT.2.5) GO TO 1
 00116      10*             DDETA  = POLY(5,A,X)
 00117      11*             RETURN
 00120      12*           1 DDETA  = B(1)*EXP(B(2)*X)
 00121      13*             RETURN
 00122      14*             END

        END OF COMPILATION:        NO  DIAGNOSTICS.
```


158685

```
@FOR,IS DDDETA
FOR S9A-07/27/72-17:45:35 (,0)

   FUNCTION DDDETA      ENTRY POINT 000036

   STORAGE USED: CODE(1) 000044; DATA(0) 000017; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003    POLY
    0004    EXP
    0005    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000016 1L        0000 R 000001 A         0000 R 000005 B          0000 R 000000 DDDETA     0000    000011 INJP$
    0003 R 000000 POLY


 00101       1*              FUNCTION  DDDETA(X)
 00101       2*       C
 00101       3*       C      D3ETA/D3NC
 00101       4*       C
 00103       5*              DIMENSION  A(4), B(2)
 00104       6*              DATA  A(1),A(2),A(3),A(4)/-0.7605300E+01,0.1518053E+02,
 00104       7*             1-0.9762402E+01,0.1985068E+01/
 00104       8*             2 B(1),B(2)/-0.8329136E-02,-0.2397718E+00/
 00113       9*              IF(X.GT.2.5) GO TO 1
 00115      10*              DDDETA  = POLY(4,A,X)
 00116      11*              RETURN
 00117      12*            1 DDDETA  = B(1)*EXP(B(2)*X)
 00120      13*              RETURN
 00121      14*              END

      END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS POLY
FOR S9A-07/27/72-17:45:42 (,0)

   FUNCTION POLY        ENTRY POINT 000036

   STORAGE USED: CODE(1) 000044; DATA(0) 000015; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000012 1076      0000   000003 INJP$     0000 I 000002 K         0000 I 000001 L         0000 R 000000 POLY


 00101      1*           FUNCTION POLY(N,A,X)
 00101      2*      C
 00101      3*      C    POLYNOMIAL EVALUATION    Y = A(N)+X*A(N-1)+X**2*A(N-2)+...
 00101      4*      C
 00103      5*           DIMENSION A(N)
 00104      6*           POLY = 0.
 00105      7*           L = N
 00106      8*           DO 1 K=1,N
 00111      9*           POLY = POLY*X+A(L)
 00112     10*         1 L = L-1
 00114     11*           RETURN
 00115     12*           END

      END OF COMPILATION:        NO  DIAGNOSTICS.
```

158687

02 @XQT
MAP 0023-07/27-17:45

ADDRESS LIMITS 001000 020432 040000 047526
STARTING ADDRESS 017366

WORDS DECIMAL 7[illegible]63 IBANK 3927 DBANK

SEGMENT MAIN		001000 020432		040000 047526
NSWTC$/FOR	1	001000 001021		
NRELK$/FOR	1	001022 001044		
NRWN[illegible]$/FOR	1	001045 001124	2	040000 040011
NWEF$/FOR	1	001125 001326	2	040012 040031
NFTCH$/FOR	1	001327 001617	2	040032 040067
NBDCL$/FOR	1	001620 001752	2	040070 040125
NFTV$/FOR	1	001753 001775		
NCNVI$/FOR	1	001776 002222	2	040126 040215
NCLOS$/FOR	1	002223 002371	2	040216 040247
NWBLK$/FOR	1	002372 002513		
NBSBL$/FOR	1	002514 002550		
NUPDA$/FOR	1	002551 002603		
NBFOC$/FOR			2	040250 042451
NININ$/FOR	1	002604 003014	2	042452 042463
NINPT$/FOR	1	003015 003657	2	042464 042503
NOTIN$/FOR	1	003660 004173	2	042504 042507
NOUT$/FOR	1	004174 005162	2	042510 042534
NFMT$/FOR	1	005163 006041	2	042535 042611
NIDER$/FOR	1	006042 006214	2	042612 042716
NFCHK$/FOR	1	006215 007076	2	042717 043055
			4	043056 043127
NTAB$/FOR			2	043130 043166
ERU$/MISC				
NIBUF$/FOR	1	007077 007141	2	043167 043167
TIR$/TECH	1	007142 007626	0	043170 043220
			2	043221 043500
NEXPS$/FOR	1	007627 007714	2	043501 043510
NIER$/FOR	1	007715 007776	2	043511 043644
NOBUF$/FOR	1	007777 010043		
ASINCOS$/FOR	1	010044 010260	0	043645 043672
SQRT$/FOR	1	010261 010321	2	043673 043704
EXP$/FOR	1	010322 010411	2	043705 043725
NERR$/FOR	1	010412 010736	2	043726 044071
BLKR (COMMON BLOCK)				044072 044103
VAB (COMMON BLOCK)				044104 044106
MCT (COMMON BLOCK)				044107 044113
BLKB (COMMON BLOCK)				044114 044115
BLKD (COMMON BLOCK)				044116 044127
BLKI (COMMON BLOCK)				044130 044153

```
BLANK$COMMON (COMMON BLOCK)
POLY                      1   010737 011002      0   044154 044170
                                                 2   BLANK$COMMON
DDDETA                    1   011003 011046      0   044171 044207
                                                 2   BLANK$COMMON
DDETA                     1   011047 011112      0   044210 044227
                                                 2   BLANK$COMMON
DETA.                     1   011113 011156      0   044230 044250
                                                 2   BLANK$COMMON
ETA                       1   011157 011222      0   044251 044272
                                                 2   BLANK$COMMON
EMINV                     1   011223 011530      0   044273 045552
                                                 2   BLANK$COMMON
INIMIX                    1   011531 011562      0   045553 045561
                          3   BLKI               2   BLANK$COMMON
INITAL                    1   011563 012304      0   045562 045704
                          3   BLKI               2   BLANK$COMMON
DERV                      1   012305 013225      0   045705 046034
                          3   BLKI               2   BLANK$COMMON
                                                 4   BLKD
MIXDER                    1   013226 013701      0   046035 046140
                          3   BLKI               2   BLANK$COMMON
                                                 4   BLKD
NCDERV                    1   013702 013745      0   046141 046153
                                                 2   BLANK$COMMON
MDER                      1   013746 014251      0   046154 046241
                                                 2   BLANK$COMMON
NDERV                     1   014252 014341      0   046242 046256
                                                 2   BLANK$COMMON
REST                      1   014342 014461      0   046257 046301
                                                 2   BLANK$COMMON
RESBND                    1   014462 014713      0   046302 046354
                                                 2   BLANK$COMMON
BNDCND                    1   014714 015324      0   046355 046441
                          3   BLK3               2   BLANK$COMMON
SCNTL                     1   015325 015520      0   046442 046455
                          3   MCT                2   BLANK$COMMON
                          5   BLKI               4   VAB
SDRV                      1   015521 016325      0   046456 046543
                          3   BLKI               2   BLANK$COMMON
                          5   BLKR               4   BLKD
                                                 6   VAB
RKS                       1   016326 017365      0   046544 046627
                                                 2   BLANK$COMMON
MAIN                      1   017366 020432      0   046630 047526
                          3   BLKI               2   BLANK$COMMON
                          5   MCT                4   BLKD
                          7   BLKB               6   BLKR

SYS$*RLIB$. LEVEL 63
END OF COLLECTION - TIME 2.084 SECONDS
```

APPENDIX C

COMPUTER CODE FOR MINIMUM

MASS OPTIMIZATION

```
@FOR,IS MAIN
FOR S9A-07/27/72-19:37:17 (,0)

   MAIN PROGRAM

   STORAGE USED: CODE(1) 001035; DATA(0) 000776; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003    BLKI    000024
    0004    BLKD    000012
    0005    MCT     000005
    0006    BLKR    000012

   EXTERNAL REFERENCES (BLOCK, NAME)

    0007    SDRV
    0010    SCNTL
    0011    CONST
    0012    NDERV
    0013    ETA
    0014    DETA
    0015    NCDERV
    0016    MDER
    0017    INTIAL
    0020    INTMIX
    0021    RKS
    0022    FMINV
    0023    BNDCND
    0024    NINTR$
    0025    NRNL$
    0026    NWDU$
    0027    NI02$
    0030    SQRT
    0031    ASIN
    0032    NI01$
    0033    NSTOP$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001    000002 1L       0001    000122 100L     0001    000273 105L     0001    000311 108L     0001    000314 109L
    0001    000321 110L     0000    000466 2000F    0000    000526 2010F    0000    000541 2040F    0000    000557 205F
    0000    000716 2050F    0000    000712 2060F    0001    001015 2070L    0000    000725 2075F    0001    001023 2090L
    0000    000733 2095F    0000    000566 210F     0000    000573 215F     0000    000654 220F     0000    000673 221F
    0000    000605 230F     0001    000462 233G     0000    000621 240F     0000    000636 250F     0001    001007 300L
    0001    001031 3000L    0001    000703 346G     0001    000725 355G     0001    000024 50L      0001    000117 90L
    0000    000534 900F     0000 R  000050 A        0000 R  000355 ALPHA    0000 R  000337 AM       0000 R  000372 AYY
    0004    000003 A1       0004    000004 A2       0004    000005 A3       0004    000006 A4       0004    000007 A5
    0004    000010 A6       0000 R  000373 BYY      0000 R  000356 DA       0014 R  000000 DETA     0000 R  000377 DETZ
    0003    000023 DE1DL    0003    000021 DE4DTB   0003 R  000013 DFM      0003 R  000012 DFMX     0003 R  000010 DFNX
    0006 R  000006 DLDNCB   0006 R  000001 DLDU     0006 R  000002 DLDV     0005 R  000000 DLMT     0000 R  000120 DLY
    0003 R  000007 DNCDT1   0000 R  000357 DR       0000 R  000414 DX       0005 R  000003 DXWRT    0000 R  000024 DY
    0000 R  000240 DYST     0000 R  000400 DYY      0000 R  000403 D2CD2T   0000 R  000404 D2CTNB   0000 R  000412 D2E4LN
    0000 R  000406 D2E4LU   0000 R  000410 D2E4LV   0000 R  000411 D2E4TN   0000 R  000405 D2E4TU   0000 R  000407 D2E4TV
```

```
0003 R 000016 D2FMLL     0006 R 000003 D2LDUU     0006 R 000004 D2LDUV     0006 R 000005 D2LDVV     0006 R 000007 D2LNCB
0006 R 000010 D2LUNB     0006 R 000011 D2LVNB     0003 R 000015 D2MDNC     0003 R 000014 D2MLNC     0003 R 000011 D2NDLL
0004 R 000001 D3M2LN     0004 R 000002 D3M2NL     0004   000011 EB       0013 R 000000 ETA        0000 R 000375 ETY
0000 R 000374 ETYY       0003   000022 E3       0003 R 000002 FM       0003 R 000003 FN         0003 R 000005 FNC
0003 R 000004 FNCBR      0000 I 000415 I        0000 I 000420 IBKP      0005 I 000001 ICNT       0000 I 000422 IERR
0000 I 000416 IFVD       0000   000426 INPUT    0000 I 000424 LCNT      0005   000004 LSTEP      0000 I 000423 LOTEP
0000 I 000417 N          0000 I 000367 NCT      0000 I 000360 NIT       0000 I 000421 NTRY       0000 R 000144 PD
0000 R 000354 PHI2       0000 R 000074 R        0000 R 000365 RHOD      0006 R 000000 RLAM       0010 R 000000 SCNTL
0000 R 000170 SD         0007 R 000000 SDRV     0000 R 000364 TFLEXT    0003 R 000000 THETAB     0000 R 000402 THETAF
0003 R 000001 THETAS     0000 R 000366 TH4      0000 R 000353 TOTMAS    0000 R 000370 T2         0000 R 000371 T3
0004 R 000000 U          0003 R 000006 V        0000 R 000334 XM        0005 R 000002 XWRT       0000 R 000000 Y
0000 R 000214 YS         0000 R 000310 YSIMP    0000 R 000264 YST       0000 R 000376 YY         0003 R 000017 Y1
0003 R 000020 Y2         0000 R 000425 ZS       0000 R 000401 ZZ        0000 R 000413 ZZZ        0000 R 000361 Z1
0000 R 000362 Z2         0000 R 000363 Z3
```

```
00100        C
00100        C
00100        C      RADIATOR SYSTEMS OPTIMIZATION FOR MINIMUM MASS
00100        C
00100        C
00101               EXTERNAL SDRV,SCNTL
00103               DIMENSION Y(20),DY(20),A(20),R(20),DLY(20),PD(20),SD(20),
00103              1          YS(20),DYST(20),YST(20),YSIMP(20),XM(3),AM(3,4)
00104               COMMON /BLKI/THETAB,THETAS,FM,FN,FNCBR,FNC,V,DNCDT1,DFNX,D2NDLL,
00104              1              DFMX,DFM,D2MLNC,D2MDNC,D2FMLL,Y1,Y2,DE4DTB,E3,DE1DL/
00104              2        BLKD/U,D3M2LN,D3M2NL,A1,A2,A3,A4,A5,A6,EB
00104              3        /MCT/DLMT,ICNT,XWRT,DXWRT,LSTEP
00104              4       /BLKR/RLAM,DLDU,DLDV,D2LDUU,D2LDUV,D2LDVV,DLDNCB,
00104              5              D2LNCB,D2LUNB,D2LVNB
00105               NAMELIST /INPUT/ THETAS,U,V,FNCBR,TOTMAS,PHI2,ALPHA,DXWRT,DA,DR
00105        C
00106               FFS(X)  = (SQRT(X*(X+2.0))+ASIN(1.0/(X+1.0))-1.570796)/X
00107               FFN(X,Y)= 1.0-Y*(0.1460*Y-0.02866)/X
00110               DFFN(X,Y)=(-0.2920*Y+0.02866)/X
00111             1 READ(5,INPUT,END=3000)
00114               NIT       =  1
00115               Z1        = U
00116               Z2        = V
00117               Z3        = FNCBR
00120               XM(1)     = 0.
00121               XM(2)     = 0.
00122               XM(3)     = 0.
00123               TFLEXT    = 2.0
00124            50 CALL CONST(TOTMAS,PHI2,ALPHA,U,V,FNCBR,RLAM,DLDU,DLDV,DLDNCB,
00124              1        D2LDUU,D2LDUV,D2LUNB,D2LDVV,D2LVNB,D2LNCB)
00125               CALL NDERV(RLAM,FN,DFNX,D2NDLL)
00126               RHOD      = RLAM
00127               WRITE(6,2000) THETAS,U,V,FNCBR,TOTMAS,PHI2,ALPHA,RLAM
00141          2000 FORMAT (1H1,10X,10HTHETA-S = F20.8/
00141              1          11X,10H      U = F20.6/
00141              2          11X,10H      V = F20.6/
00141              3          11X,10H  FNCBR = F20.6/
00141              4          11X,10H TOTMAS = F20.6/
00141              5          11X,10H   PHI2 = F20.6/
```

```
00141          6              11X,10H  ALPHA = F20.6/
00141          9              11X,10H LAMBDA = F20.6///)
00142            WRITE(6,2010) NIT
00145       2010 FORMAT (5X'NUMBER OF ITERATIONS = 'I2)
00146            TH4      = THETAS**4
00147            IF(V.GT.0.2) GO TO 90
00151            IF(V.LE.1.0E-10) GO TO 108
00153         90 THETAB   = 0.9
00154         95 NCT      = 0
00155        100 T2       = THETAB**2
00156            T3       = T2*THETAB
00157            FNC      = FNCBR*T3
00160            FM       = FFN(RHOD,FNC)*FFS(RHOD)
00161            DFM      = DFFN(RHOD,FNC)*FFS(RHOD)
00162            AYY      = T3*THETAB-TH4
00163            BYY      = 1.0-THETAB
00164            ETYY     = ETA(FNC)
00165            ETY      = ETYY*FM+FN
00166            YY       = 1.0/V-ETY*AYY/BYY
00167            DETZ     = (DFM*ETYY+FM*DETA(FNC))*3.0*T2*FNCBR
00170            DYY      = -AYY/BYY*(DETZ+ETY/BYY)-4.0*ETY*T3/BYY
00171            ZZ       = THETAB-YY/DYY
00172            IF(NCT.GT.20) GO TO 109
00174            IF(ZZ.LT.1.0) GO TO 105
00176            THETAB   = (THETAB+1.0)/2.0
00177            NCT      = NCT+1
00200            GO TO 100
00201        105 IF(ABS(ZZ-THETAB)/ZZ.LT.1.0E-06) GO TO 110
00203            NCT            = NCT+1
00204            THETAB   = ZZ
00205            GO TO 100
00206        108 THETAB         = 1.0
00207            GO TO 110
00210        109 WRITE(6,900)
00210      C
00212        110 Y(1)     = 1.0
00213            Y(2)     = THETAB
00214        900 FORMAT(1H0,20HNEWTON-RAPHSON FAILS)
00215            THETAF   = Y(1)
00216            T1       = Y(1)
00217            Y2       = Y(2)
00220            CALL NCDERV(FNCBR,THETAB,FNC,DNCDT1,D2CD2T,D2CTNR)
00221            CALL MDER(RLAM,FNC,FM,DFMX,DFM,D2FMLL,D2MDNC,D2MLNC,D3M2LN,D3M2NL)
00222            CALL INTIAL(DLDU,D2LDUU,Y(3),Y(4),Y(5),Y(6),0.,1.,D2E4TU,D2E4LU)
00223            CALL INTIAL(DLDV,D2LDVV,Y(7),Y(8),Y(9),Y(10),0.,0.,D2E4TV,D2E4LV)
00224            CALL INTIAL(DLDNCB,D2LNCB,Y(11),Y(12),Y(13),Y(14),1.,1.,D2E4TN,
00224          1                D2E4LN)
00225            CALL INTMIX(D2E4TV,Y(4),DLDU,D2E4LV,D2LDUV,Y(16),Y(15))
00226            CALL INTMIX(D2E4TN,Y(4),DLDU,D2E4LN,D2LUNB,Y(18),Y(17))
00227            CALL INTMIX(D2E4TN,Y(8),DLDV,D2E4LN,D2LVNB,Y(20),Y(19))
00230            ZZZ      = 0
00231            DLMT     = DX/500.
00232            DO 115 I=1,20
00235            A(I)     = DA
00236        115 R(I)     = DR
00236      C
00240            WRITE(6,2040)
```

```
00242        2040 FORMAT(/7X,6HTHETAF,10X,6HTHETAB,10X,2HNC,13X,6HETABAR,
00242           1       11X,3HETA,13X,1HM,14X,1HN,14X,1HX/)
00242       C
00243             ZZZ      = 0.0
00244             DX       = 1.0/(U*(1.0-THETAB))
00245             IFVD     = 0
00246             IF(DX.GT.DXWRT) DX = DXWRT
00250             N        = 20
00251             IBKP     = 1
00252             NTRY     = 1
00253             IERR     = 0
00253       C
00254             DLMT     = DXWRT/500.0
00255             XWRT     = 0.0
00256             LOTEP    = 0
00257             LCNT     = 0
00260             ICNT     = 0
00261             CALL RKS(SDRV,SCNTL,Y,DY,A,R,ZZZ,DX,N,IFVD,IBKP,NTRY,IERR,
00261          1          DLY,PD,SD,YS,YST,DYST,YSIMP)
00262             XM(1)    =  -Y(3)
00263             XM(2)    =  -Y(7)
00264             XM(3)    =  -Y(11)
00265             AM(1,1) =  Y(5)
00266             AM(1,2) =  Y(15)
00267             AM(1,3) =  Y(17)
00270             AM(2,1) =  Y(15)
00271             AM(2,2) =  Y(9)
00272             AM(2,3) =  Y(19)
00273             AM(3,1) =  Y(17)
00274             AM(3,2) =  Y(19)
00275             AM(3,3) =  Y(13)
00276             CALL FMINV(AM,XM,3,4)
00277         205 FORMAT (///45X,27H PARAMETERS AT END OF TUBE //)
00300         210 FORMAT (1X,51X,8HTHETAF =,F10.6,/)
00301         215 FORMAT (1X,23X,3HU =,E14.6,16X,3HV =,E14.6,12X,7HNCBAR =,E14.6,/)
00302         230 FORMAT (1X,19X,7HDTFDU =,E14.6,12X,7HDTFDV =,E14.6,8X,
00302          1          11HDTFNCBAR =,E14.6,/)
00303         240 FORMAT (1X,17X,9HD2TFD2U =,E14.6,10X,9HD2TFD2V =,E14.6,6X,
00303          1          13HD2TFD2NCBAR =,E14.6,/)
00304         250 FORMAT (1X,16X,10HD2TFDUDV =,E14.6,5X,14HD2TFDUDNCBAR =,E14.6,
00304          1          5X,14HD2TFDVDNCBAR =,E14.6,/)
00305         220 FORMAT (/,3X,24HINCR. SOUGHT    DELTA U =,E14.6,10X,9HDELTA V =,
00305          1            E14.6,6X,13HDELTA NCBAR =,E14.6/)
00306         221 FORMAT (/,3X,24HINCR. USED      DELTA U =,E14.6,10X,9HDELTA V =,
00306          1            E14.6,6X,13HDELTA NCBAR =,E14.6/)
00307             NIT      =  NIT+1
00310             Z1       = U
00311             Z2       = V
00312             Z3       = FNCBR
00313             WRITE (6,205)
00315             WRITE (6,210) Y(1)
00320             WRITE (6,215) Z1,Z2,Z3
00325             WRITE (6,230) Y(3),Y(7),Y(11)
00332             WRITE (6,240) Y(5),Y(9),Y(13)
00337             WRITE (6,250) Y(15),Y(17),Y(19)
00344             WRITE(6,220) (XM(I),I=1,3)
00352             CALL BNDCND(U,V,FNCBR,XM,TOTMAS,ALPHA)
```

```
00353                WRITE(6,221) (XM(I),I=1,3)
00361           200  IF (NIT .GT. 20) GO TO 300
00363                ZS       = Y(1)-THETAS
00364                IF(ZS.LT.0.0001) GO TO 2070
00366                IF(ABS(Y(1)-TFLEXT)/Y(1) .LE. 5.0E-04) GO TO 2090
00370                TFLEXT  = Y(1)
00371                IF (ABS(XM(1))/Z1.GT.0.0001) GO TO 50
00373                IF (ABS(XM(2))/Z2.GT.0.0001) GO TO 50
00375                IF (ABS(XM(3))/Z3.GT.0.0001) GO TO 50
00377                WRITE(6,2060)
00401          2060  FORMAT(1H0,15HOPTIMUM REACHED)
00402                GO TO 1
00403           300  WRITE (6,2050)
00405          2050  FORMAT (1X,32H NUMBER OF ITERATIONS EXCEEDS 20 )
00406                GO TO 1
00407          2070  WRITE(6,2075)
00411          2075  FORMAT(1H0,24HVANISHING HEAT REJECTION)
00412                GO TO 1
00413          2090  WRITE(6,2095)
00415          2095  FORMAT(1H0,40HINSIGNIFICANT IMPROVEMENT OVER LAST STEP)
00416                GO TO 1
00417          3000  STOP
00420                END

       END OF COMPILATION:       NO  DIAGNOSTICS.
```

177028

```
@FOR,IS CONST
FOR S9A=07/27/72-19:37:44 (,0)

   SUBROUTINE CONST      ENTRY POINT 000373

   STORAGE USED: CODE(1) 000446; DATA(0) 000071; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   SQRT
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000003 A        0000 R 000002 AZ       0000 R 000004 B        0000 R 000005 C        0000 R 000006 D
    0000 R 000010 DAN      0000 R 000007 DAV      0000 R 000014 DBN      0000 R 000013 DBV      0000 R 000017 DCU
    0000 R 000020 DCV      0000 R 000026 DDN      0000 R 000024 DDU      0000 R 000025 DDV      0000 R 000023 DZ
    0000 R 000012 D2ANN    0000 R 000031 D2AVN    0000 R 000011 D2AVV    0000 R 000016 D2BNN    0000 R 000032 D2BVN
    0000 R 000015 D2BVV    0000 R 000021 D2CUU    0000 R 000033 D2CUV    0000 R 000022 D2CVV    0000 R 000030 D2DNN
    0000 R 000034 D2DVN    0000 R 000027 D2DVV    0000   000043 INJP$    0000 R 000000 PI       0000 R 000001 Z


 00101          SUBROUTINE CONST(TOTMAS,PHI2,ALPHA,U,V,FNCBR,HOD,DLDU,DLDV,DLDNCB,
 00101         1                 D2LDUU,D2LDUV,D2LUNB,D2LDVV,D2LVNB,D2LNCB)
 00101     C
 00103          PI       = 3.1415926
 00104          Z        = V**3/FNCBR
 00105          AZ       = ALPHA*ALPHA
 00106          A        = TOTMAS-AZ*Z
 00107          IF (A .LT. 1.0E-06)  A = 1.0E-06
 00107     C
 00111       50 B        = PI*ALPHA*Z
 00112          C        = PHI2*ALPHA*V**2*SQRT(U)
 00113          D        = SQRT(B*B+A*C)
 00114          HOD      = (B+D)/A
 00114     C
 00115          DAV      = -3.0*B*ALPHA/(PI*V)
 00116          DAN      = AZ*Z/FNCBR
 00117          D2AVV    = -6.0*AZ*V/FNCBR
 00120          D2ANN    = -2.0*DAN/FNCBR
 00120     C
 00121          DBV      = 3.0*B/V
 00122          DBN      = -B/FNCBR
 00123          D2BVV    = 6.0*B/(V*V)
 00124          D2BNN    = 2.0*B/(FNCBR*FNCBR)
 00124     C
 00125          DCU      = C/(2.0*U)
 00126          DCV      = 2.0*C/V
 00127          D2CUU    = -DCU/(2.0*U)
 00130          D2CVV    = DCV/V
 00130     C
```

```
00131      30*              DZ      = 2.0*D
00132      31*              DDU     = A*DCU/DZ
00133      32*              DDV     = (2.0*B*DBV+A*DCV+C*DAV)/DZ
00134      33*              DDN     = (2.0*B*DBN+C*DAN)/DZ
00135      34*              D2DVV   = (-DDV*DDV+DBV*DBV+B*D2BVV+DAV*DCV+(D2CVV*A+D2AVV*C)/2.0)
00135      35*         1              /D
00136      36*              D2DNN   = (-DDN*DDN+DBN*DBN+B*D2BNN+C*D2ANN/2.0)/D
00136      37*        C
00137      38*              D2AVN   = -3.0*DBN*ALPHA/(PI*V)
00140      39*              D2BVN   = 3.0*DBN/V
00141      40*              D2CUV   = C/(U*V)
00142      41*              D2DVN   = (-DDN*DDV+DBV*DBN+B*D2BVN+(DCV*DAN+C*D2AVN)/2.0)/D
00142      42*        C
00143      43*              DLDU    = DCU/DZ
00144      44*              DLDV    = (-HOD*DAV+DBV+DDV)/A
00145      45*              DLDNCB  = (-HOD*DAN+DBN+DDN)/A
00145      46*        C
00146      47*              D2LDUU  = (D2CUU-DDU*DCU/D)/DZ
00147      48*              D2LDVV  = (-2.0*DLDV*DAV-HOD*D2AVV+D2BVV+D2DVV)/A
00150      49*              D2LNCB  = (-2.0*DLDNCB*DAN-HOD*D2ANN+D2BNN+D2DNN)/A
00150      50*        C
00151      51*              D2LDUV  = (D2CUV-2.0*DLDU*DDV)/DZ
00152      52*              D2LUNB  = -DLDU*DDN/D
00153      53*              D2LVNB  = (-DLDV*DAN-DLDNCB*DAV-HOD*D2AVN+D2BVN+D2DVN)/A
00154      54*              RETURN
00155      55*              END

         END OF COMPILATION:        NO  DIAGNOSTICS.
```

177938

```
@FOR,IS BNDCND
FOR S9A-07/27/72-19:37:47 (,0)

SUBROUTINE BNDCND    ENTRY POINT 000154

STORAGE USED: CODE(1) 000207; DATA(0) 000027; BLANK COMMON(2) 000000

EXTERNAL REFERENCES (BLOCK, NAME)

 0003   NEXP6$
 0004   NERR3$

STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

 0001    000011 500L      0000    000014 INJP$      0000 I 000000 L        0000 R 000004 X1        0000 R 000005 X2
 0000 R 000001 Z1        0000 R 000002 Z2        0000 R 000003 Z3


00101      1*           SUBROUTINE BNDCND(U,V,FNCBR,XM,TOTMAS,ALPHA)
00101      2*      C
00101      3*      C    BNDCND INSURES U,V, AND NCBAR ARE WITHIN THEIR BOUNDARY CONDITIONS
00101      4*      C
00103      5*           DIMENSION XM(3)
00104      6*           L       = 1
00105      7*           Z1      = U
00106      8*           Z2      = V
00107      9*           Z3      = FNCBR
00110     10*       500 U       = Z1+XM(1)
00111     11*           V       = Z2+XM(2)
00112     12*           FNCBR   = Z3+XM(3)
00113     13*           IF(L.EQ.2) RETURN
00113     14*      C
00115     15*           IF(U.LT.5.0E-06)        XM(1) = 5.0E-06-Z1
00117     16*           IF(U.GT.250.0)          XM(1) = 250.0-Z1
00121     17*           IF(V.LT.5.0E-06)        XM(2) = 5.0E-06-Z2
00123     18*           IF(V.GT. 50.0)          XM(2) =  50.0-Z2
00125     19*           IF(FNCBR.LT.1.0E-04)    XM(3) = 1.0E-04-Z3
00127     20*           IF(FNCBR.GT.6.0)        XM(3) = 6.0-Z3
00131     21*           X1      = TOTMAS*FNCBR
00132     22*           X2      = ALPHA**2
00133     23*           IF(X1-X2*V**3.LT.0.0)  XM(2) = (X1/X2)**(1.0/3.0)-Z2
00135     24*           L       = 2
00136     25*           GO TO 500
00137     26*           END

     END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS NDERV
FOR S9A-07/27/72-19:37:49 (,0)

   SUBROUTINE NDERV     ENTRY POINT 000056

   STORAGE USED: CODE(1) 000070; DATA(0) 000015; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   SQRT
    0004   ASIN
    0005   NERR3$

   STORAGE ASSIGNMENT (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000000 C4       0000 R 000001 C5       0000 R 000002 C6       0000   000006 INJP$


00101      1*              SUBROUTINE NDERV(RLAM,FN,DFNX,D2NDLL)
00101      2*        C
00101      3*        C     N AND ITS DERIVATIVES
00101      4*        C
00103      5*              C4      = RLAM+1.0
00104      6*              C5      = RLAM+2.0
00105      7*              C6      = SQRT(RLAM*C5)
00106      8*              FN      =-(1.5707963+C5-C6-ASIN(1.0/C4))/RLAM
00107      9*              DFNX    = -(FN+C6/C4-1.0)/RLAM
00110     10*              D2NDLL  = -(2.0*DFNX+1.0/(C4*C4*C6))/RLAM
00111     11*              RETURN
00112     12*              END

       END OF COMPILATION:        NO  DIAGNOSTICS.
```


177937

```
@FOR,IS MDER
FOR S9A-07/27/72-19:37:57 (,0)

   SUBROUTINE MDER       ENTRY POINT 000251

   STORAGE USED: CODE(1) 000304; DATA(0) 000066; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

     0003   SQRT
     0004   ASIN
     0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

     0000 R 000011 CFN      0000 R 000000 C1      0000 R 000017 C10     0000 R 000020 C11     0000 R 000022 C12
     0000 R 000001 C2       0000 R 000003 C3      0000 R 000002 C4      0000 R 000004 C5      0000 R 000005 C6
     0000 R 000006 C7       0000 R 000007 C8      0000 R 000010 C9      0000 R 000015 DCFDNC  0000 R 000013 DCFNDL
     0000 R 000014 DFFSDL   0000 R 000016 D2CFLL  0000 R 000025 D2CFNC  0000 R 000026 D2CLNC  0000 R 000023 D2C2LL
     0000 R 000021 D2C3LL   0000 R 000024 D2FSLL  0000 R 000027 D3C2LN  0000 R 000030 D3C2NL  0000 R 000012 FFS
     0000   000040 INJP$


00101               SUBROUTINE MDER(RLAM,FNC,FM,DFMX,DFM,D2FMLL,D2MDNC,D2MLNC,D3M2LN,
00101              1D3M2NL)
00101          C
00101          C    M AND ITS DERIVATIVES
00101          C
00103               C1       = 0.1460*FNC-0.02866
00104               C2       = SQRT(RLAM*(2.+RLAM))
00105               C4       = 1.0/(RLAM+1.0)
00106               C3       = ASIN(C4)
00107               C5       = 1/(C4*C2)
00110               C6       = (C4**2)/SQRT(1-C4**2)
00111               C7       = 1/(RLAM**2)
00112               C8       = FNC/RLAM
00113               C9       = 2.*C7*C8
00114               CFN      = 1.0-C1*C8
00115               FFS      = (C2+C3-1.57079635)/RLAM
00116               FM       = CFN*FFS
00117               DCFNDL   = C1*C7*FNC
00120               DFFSDL   = (C5-C6-FFS)/RLAM
00121               DFMX     = CFN*DFFSDL+FFS*DCFNDL
00122               DCFDNC   = -(0.1460*FNC+C1)/RLAM
00123               DFM      = FFS*DCFDNC
00124               D2CFLL   = -C1*C9
00125               C10      = 1-C4**2
00126               C11      = +1.+0.5/C10*C4**2
00127               D2C3LL   = 2*(C4**3)*C11/SQRT(C10)
00130               C12      = 1/C2-C2*(C4**2)
00131               D2C2LL   = -C12/(C4*C2)**2
```

```
      D2FSLL  = (D2C2LL+D2C3LL-2.*DFFSDL)/RLAM
      D2FMLL  = CFN*D2FSLL+2.*DFFSDL*DCFNDL+FFS*D2CFLL
      D2CFNC  = -0.2920/RLAM
      D2MDNC  = FFS*D2CFNC
      D2CLNC  = (0.146*FNC+C1)*C7
      D2MLNC  = DCFDNC*DFFSDL+D2CLNC*FFS
      D3C2LN  = -2.*D2CLNC/RLAM
      D3M2LN  = DCFDNC*D2FSLL+2.*DFFSDL*D2CLNC+FFS*D3C2LN
      D3C2NL  = 0.2920*C7
      D3M2NL  = FFS*D3C2NL+DFFSDL*D2CFNC
      RETURN
      END
```

END OF COMPILATION: NO DIAGNOSTICS.

```
@FOR,IS INTIAL
FOR S9A-07/27/72-19:38:01 (,0)

   SUBROUTINE INTIAL    ENTRY POINT 000470

   STORAGE USED: CODE(1) 000522; DATA(0) 000123; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003    BLKI    0000:4

   EXTERNAL REFERENCES (BLOCK, NAME)

    0004    ETA
    0005    DETA
    0006    DDETA
    0007    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000037 A1       0000 R 000040 A2       0000 R 000041 A3       0000 R 000053 B1       0000 R 000054 B2
    0006 R 000000 DDETA    0000 R 000051 DDETDU   0005 R 000000 DETA     0000 R 000046 DETADU   0003 R 000023 DE1DL
    0000 R 000032 DE1DUC   0000 R 000027 DE1DTB   0000 R 000047 DE1DU    0000 R 000030 DE2DTB   0000 R 000034 DE2DU
    0000 R 000031 DE3DTB   0000 R 000035 DE3DU    0003 R 000021 DE4DTB   0000 R 000033 DE4DU    0000 R 000044 DFCNDU
    0003 R 000013 DFM      0000 R 000045 DFMDU    0003 R 000012 DFMX     0000 R 000043 DFNDU    0003 R 000010 DFNX
    0003 R 000007 DNCDT1   0000 R 000061 D1       0000 R 000062 D2       0000 R 000065 D2E1CB   0000 R 000060 D2E1LU
    0000 R 000055 D2E1TU   0000 R 000036 D2E2TU   0000 R 000042 D2E3TU   0000 R 000066 D2E4CB   0000 R 000071 D2E4UU
    0003 R 000016 D2FMLL   0000 R 000056 D2MDLU   0003 R 000015 D2MDNC   0003 R 000014 D2MLNC   0000 R 000052 D2MNCU
    0000 R 000067 D2NCUB   0000 R 000050 D2NCTU   0003 R 000011 D2NDLL   0000 R 000057 D2NDLU   0000 R 000063 D3
    0000 R 000064 D4       0004 R 000000 ETA      0000 R 000025 E1       0000 R 000026 E2       0003 R 000022 E3
    0003 R 000002 FM       0003 R 000003 FN       0003 R 000005 FNC      0003 R 000004 FNCBR    0000   000100 INJP$
    0000 R 000070 TERMUB   0003 R 000000 THETAB   0003 R 000001 THETAS   0003 R 000006 V        0000 R 000000 Y
    0003 R 000017 Y1       0003 R 000020 Y2       0000 R 000024 Z


  00101      1*          SUBROUTINE INTIAL(DLDU,D2LDUU,Y3,Y4,Y5,Y6,B,C,D2E4TU,D2E4LU)
  00101      2*     C
  00101      3*     C    INTIAL CONDITIONS
  00101      4*     C
  00101      5*     C    FOR FIRST AND SECOND DERIVATIVES OF     U SET C=1 AND B=0
  00101      6*     C    FOR FIRST AND SECOND DERIVATIVES OF     V SET C=0 AND B=0
  00101      7*     C    FOR FIRST AND SECOND DERIVATIVES OF FNCBR SET C=1 AND B=1
  00101      8*     C
  00103      9*          DIMENSION Y(20)
  00104     10*          COMMON /BLKI/THETAB,THETAS,FM,FN,FNCBR,FNC,V,DNCDT1,DFNX,D2NDLL,
  00104     11*         1          DFMX,DFM,D2MLNC,D2MDNC,D2FMLL,Y1,Y2,DE4DTB,E3,DE1DL
  00105     12*          Y(1)     = Y1
  00106     13*          Y(2)     = Y2
  00107     14*          Z        = FNC
  00110     15*          E1       = FM*ETA(Z)+FN
  00111     16*          E2       = THETAB**4-THETAS**4
```

```
      E3     = E2/(1-THETAB)
      Y(3)   = 0.
      DE1DTB = DNCDT1*(DFM*ETA(Z)+FM*DETA(Z))
      DE2DTB = 4.*(THETAB**3)
      DE3DTB = E3*(DE2DTB+E3)/E2
      DE4DTB = E1*DE3DTB+E3*DE1DTB
      DE1DL  = ETA(Z)*DFMX+DFNX
      DE1DNC = ETA(Z)*DFM+DETA(Z)*FM
      DE4DU  = E3*DE1DL*DLDU+B*E3*DE1DNC*THETAB**3
      Y(4)   = -((1-C)/V**2+DE4DU)/DE4DTB
      Y(5)   = 0.
      DE2DU  = DE2DTB*Y(4)
      DE3DU  = E3*(E3*Y(4)+DE2DU)/E2
      D2E2TU = 12.*Y(4)*(THETAB**2)
      A1     = E3*(D2E2TU+DE3DU)/E2
      A2     = DE2DTB+E3
      A3     = -E3*DE2DU/(E2**2)+DE3DU/E2
      D2E3TU = A1+A2*A3
      DFNDU  = DFNX*DLDU
      DFCNDU = DNCDT1*Y(4)+B*Y(2)**3
      DFMDU  = DFMX*DLDU+DFM*DFCNDU
      DETADU = DETA(Z)*DFCNDU
      DE1DU  = FM*DETADU+ETA(Z)*DFMDU+DFNDU
      D2NCTU = 6*FNCBR*Y(2)*Y(4)+B*3*Y(2)**2
      DDETDU = DDETA(Z)*DFCNDU
      D2MNCU = D2MLNC*DLDU+D2MDNC*DFCNDU
      B1     = DFM*DETADU+ETA(Z)*D2MNCU+FM*DDETDU+DETA(Z)*DFMDU
      B2     = DE1DTB*D2NCTU/DNCDT1
      D2E1TU = DNCDT1*B1+B2
      D2MDLU = D2FMLL*DLDU+D2MLNC*DFCNDU
      D2NDLU = D2NDLL*DLDU
      D2E1LU = ETA(Z)*D2MDLU+DETADU*DFMX+D2NDLU
      D2E4LU = E3*D2E1LU+DE1DL*DE3DU
      D1     = DETA(Z)*DFCNDU*DFM
      D2     = ETA(Z)*D2MNCU
      D3     = DDETA(Z)*FM*DFCNDU
      D4     = DETA(Z)*DFMDU
      D2E1CB = D1+D2+D3+D4
      D2E4CB = DE3DU*DE1DNC+E3*D2E1CB
      D2NCNB = 3*Y(4)*Y(2)**2
      TERMNB = B*(E3*DE1DNC*D2NCNB+Y(2)**3*D2E4CB)
      D2E4UU = E3*DE1DL*D2LDUU+DLDU*D2E4LU+TERMNB
      D2E4TU = E1*D2E3TU+DE3DTB*DE1DU+E3*D2E1TU+DE1DTB*DE3DU
      Y(6)   = -(Y(4)*D2E4TU+D2E4UU+2*(C-1)/V**3)/DE4DTB
      Y3     = Y(3)
      Y4     = Y(4)
      Y5     = Y(5)
      Y6     = Y(6)
      RETURN
      END

END OF COMPILATION:        NO  DIAGNOSTICS.
```

177941

```
@FOR,IS DERV
FOR S9A-07/27/72-19:38:07 (,0)

    SUBROUTINE DERV       ENTRY POINT 000604

    STORAGE USED: CODE(1) 000721; DATA(0) 000130; BLANK COMMON(2) 000000

     COMMON BLOCKS:

     0003    BLKI    000024
     0004    BLKD    000012

    EXTERNAL REFERENCES (BLOCK, NAME)

     0005    ETA
     0006    DETA
     0007    DDETA
     0010    DDDETA
     0011    NERR3$

    STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

     0004 R 000003 A1        0004 R 000004 A2        0004 R 000005 A3        0004 R 000006 A4        0004 R 000007 A5
     0004 R 000010 A6        0000 R 000051 A7        0000 R 000063 DA7DU     0010 R 000000 DDDETA    0007 R 000000 DDETA
     0006 R 000000 DETA      0003   000023 DE1DL     0003   000021 DE4DTB    0003 R 000013 DFM       0003 R 000012 DFMX
     0003 R 000010 DFNX      0003   000007 DNCDT1    0000 R 000052 DNDU      0000 R 000024 DY        0000 R 000053 D2A1UU
     0000 R 000066 D2A2UU    0000 R 000067 D2A3UU    0000 R 000070 D2A4UU    0000 R 000061 D2A5UU    0000 R 000062 D2A6U
     0000 R 000065 D2EEUU    0000 R 000055 D2EPUU    0000 R 000060 D2EUU     0003 R 000016 D2FMLL    0003 R 000015 D2MDNC
     0003 R 000014 D2MLNC    0000 R 000056 D2MUU     0000 R 000054 D2NCUU    0003 R 000011 D2NDLL    0000 R 000064 D2NUU
     0000 R 000057 D3MNUU    0004 R 000001 D3M2LN    0004 R 000002 D3M2NL    0004 R 000011 EB        0005 R 000000 ETA
     0003   000022 E3        0003 R 000002 FM        0003 R 000003 FN        0003 R 000005 FNC       0003 R 000004 FNCBR
     0000   000077 INJP$     0003   000000 THETAB    0003 R 000001 THETAS    0004 R 000000 U         0003   000006 V
     0000 R 000000 Y         0003 R 000017 Y1        0003 R 000020 Y2        0000 R 000050 Z
```

```
00101                    SUBROUTINE DERV(Y3,Y4,Y5,Y6,DLDU,D2LDUU,DY3,DY4,DY5,DY6,B,C,
00101                   1                DNCDU,DA1DU,DA2DU,DA3DU,DA4DU,DA5DU,DA6DU,
00101                   2                DEBDU,DEU,DEPU,DMDU,D2MNCU)
00101              C
00101              C      DERIVATIVES
00101              C
00101              C     FOR FIRST AND SECOND DERIVATIVES OF     U SET C=1 AND B=0
00101              C     FOR FIRST AND SECOND DERIVATIVES OF     V SET C=0 AND B=0
00101              C     FOR FIRST AND SECOND DERIVATIVES OF FNCBR SET C=0 AND B=1
00101              C
00103                    DIMENSION Y(20),DY(20)
00104                    COMMON /BLKI/THETAB,THETAS,FM,FN,FNCBR,FNC,V,DNCDT1,DFNX,D2NDLL,
00104                   1              DFMX,DFM,D2MLNC,D2MDNC,D2FMLL,Y1,Y2,DE4DTB,E3,DE1DL/
00104                   2          BLKD/U,D3M2LN,D3M2NL,A1,A2,A3,A4,A5,A6,EB
00105                    Y(1)     = Y1
00106                    Y(2)     = Y2
```

```
      Y(3)    = Y3
      Y(4)    = Y4
      Y(5)    = Y5
      Y(6)    = Y6
      Z       = FNC
      EB      = FM*ETA(Z)+FN
      A1      = 1./(Y(1)-Y(2))
      A5      = FM*DETA(Z)+ETA(Z)*DFM
      A6      = 3*Y(2)**2*FNCBR
      A2      = A6*A5/EB
      A3      = 4*Y(2)**3/(Y(2)**4-THETAS**4)
      A4      = A1+A2+A3
      DA1DU   = -A1**2*(Y(3)-Y(4))
      DNCDU   = A6*Y(4)+B*Y(2)**3
      DEPU    = DDETA(Z)*DNCDU
      DMDU    = DFMX*DLDU+DFM*DNCDU
      D2MNCU  = D2MLNC*DLDU+D2MDNC*DNCDU
      DEU     = DETA(Z)*DNCDU
      DA5DU   = FM*DEPU+DETA(Z)*DMDU+ETA(Z)*D2MNCU+DFM*DEU
      DA6DU   = 6*Y(2)*FNCBR*Y(4)+B*3*Y(2)**2
      A7      = A6*DA5DU+A5*DA6DU
      DNDU    = DFNX*DLDU
      DEBDU   = FM*DEU+ETA(Z)*DMDU+DNDU
      DA2DU   = (A7-A2*DEBDU)/EB
      DA3DU   = A3*Y(4)*(3/Y(2)-A3)
      DA4DU   = DA1DU+DA2DU+DA3DU
      DY(4)   = -C/A4+U/A4**2*DA4DU
      D2A1UU  = -A1**2*(Y(5)-Y(6))-2*A1*DA1DU*(Y(3)-Y(4))
      D2NCUU  = A6*Y(6)+DA6DU*Y(4)+B*3*Y(4)*Y(2)**2
      D2EPUU  = DDETA(Z)*D2NCUU+DNCDU**2*DDDETA(Z)
      D2MUU   = DFMX*D2LDUU+DLDU*(D2FMLL*DLDU+D2MLNC*DNCDU)+DFM*D2NCUU
     1        +DNCDU*(D2MLNC*DLDU+D2MDNC*DNCDU)
      D3MNUU  = D2MLNC*D2LDUU+DLDU*(D3M2LN*DLDU+D3M2NL*DNCDU)
     1        +D2MDNC*D2NCUU+DNCDU*D3M2NL*DLDU
      D2EUU   = DETA(Z)*D2NCUU+DDETA(Z)*DNCDU**2
      D2A5UU  = FM*D2EPUU+2*DEPU*DMDU+DETA(Z)*D2MUU+ETA(Z)*D3MNUU
     1        +2*DEU*D2MNCU+DFM*D2EUU
      D2A6U   = 6*Y(2)*FNCBR*Y(6)+6*FNCBR*Y(4)**2+B*12*Y(2)*Y(4)
      DA7DU   = A6*D2A5UU+DA5DU*DA6DU+A5*D2A6U+DA6DU*DA5DU
      D2NUU   = DFNX*D2LDUU+D2NDLL*DLDU**2
      D2EBUU  = FM*D2EUU+2*DEU*DMDU+ETA(Z)*D2MUU+D2NUU
      D2A2UU  = (DA7DU-A2*D2EBUU-2*DEBDU*DA2DU)/EB
      D2A3UU  = A3*((3/Y(2)-A3)*Y(6)+Y(4)*(-3/Y(2)**2*Y(4)-DA3DU)
     1        +(1/A3*DA3DU)**2)
      D2A4UU  = D2A1UU+D2A2UU+D2A3UU
      DY(6)   = -2/A4*DY(4)*DA4DU+U/A4**2*D2A4UU
      DY(3)   = U*(Y(4)-Y(3))+(Y(2)-Y(1))*C
      DY(5)   = U*(Y(6)-Y(5))+2*(Y(4)-Y(3))*C
      DY3     = DY(3)
      DY4     = DY(4)
      DY5     = DY(5)
      DY6     = DY(6)
      RETURN
      END

END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS INTMIX
FOR S9A-07/27/72-19:38:11 (,0)

   SUBROUTINE INTMIX    ENTRY POINT 000024

   STORAGE USED: CODE(1) 000032; DATA(0) 000007; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003   BLKI    000024

   EXTERNAL REFERENCES (BLOCK, NAME)

    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0003 R 000023 DE1DL     0000 R 000000 DE4DL     0003 R 000021 DE4DTB    0000 R 000001 DE4DXY    0003   000013 DFM
    0003   000012 DFMX      0003   000010 DFNX      0003   000007 DNCDT1    0003   000016 D2FMLL    0003   000015 D2MDNC
    0003   000014 D2MLNC    0003   000011 D2NDLL    0003 R 000022 E3        0003   000002 FM        0003   000003 FN
    0003   000005 FNC       0003   000004 FNCBR     0000   000002 INJP$     0003   000000 THETAB    0003   000001 THETAS
    0003   000006 V         0003   000017 Y1        0003   000020 Y2


00101      1*          SUBROUTINE INTMIX(D2E4TY,DTBDX,DLDX,D2E4LY,D2LDXY,D2TBXY,D2TFXY)
00103      2*          COMMON /BLKI/THETAB,THETAS,FM,FN,FNCBR,FNC,V,DNCDT1,DFNX,D2NDLL,
00103      3*         1         DFMX,DFM,D2MLNC,D2MDNC,D2FMLL,Y1,Y2,DE4DTB,E3,DE1DL
00104      4*          D2TFXY  = 0.
00105      5*          DE4DL   = E3*DE1DL
00106      6*          DE4DXY  = D2E4LY*DLDX+DE4DL*D2LDXY
00107      7*          D2TBXY  = -(DE4DXY+DTBDX*D2E4TY)/DE4DTB
00110      8*          RETURN
00111      9*          END

       END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS MIXDER
FOR S9A-07/27/72-19:38:18 (,0)

   SUBROUTINE MIXDER     ENTRY POINT 000347

   STORAGE USED: CODE(1) 000454; DATA(0) 000104; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003   BLKI    000024
    0004   BLKD    000012

   EXTERNAL REFERENCES (BLOCK, NAME)

    0005   DDETA
    0006   DETA
    0007   DDDETA
    0010   ETA
    0011   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0004 R 000003 A1       0004 R 000004 A2       0004 R 000005 A3       0004 R 000006 A4       0004 R 000007 A5
    0004 R 000010 A6       0007 R 000000 DDDETA   0005 R 000000 DDETA    0006 R 000000 DETA     0003   000023 DE1DL
    000:   000021 DE4D19   0003 R 000013 DFM      0003 R 000012 DFMX     0003 R 000010 DFNX     0003   000007 DNCDT1
    0000 R 000006 DNCD>Y   0000 R 000003 D2A1XY   0000 R 000020 D2A2XY   0000 R 000021 D2A3XY   0000 R 000022 D2A4XY
    0000 R 000015 D2A5>Y   0000 R 000004 D2A6XY   0000 R 000017 D2EBXY   0000 R 000012 D2EPXY   0000 R 000011 D2EXY
    0003 R 000016 D2FMLL   0000 R 000013 D2MDLY   0003 R 000015 D2MDNC   0000 R 000014 D2MDXY   0003 R 000014 D2MLNC
    0003 R 000011 D2NDLL   0000 R 000016 D2NDXY   0000 R 000007 D3MNLY   0000 R 000010 D3MNXY   0004 R 000001 D3M2LN
    0004 R 000002 D3M2NL   0000 R 000005 D3M2NY   0004 R 000011 EB       0010 R 000000 ETA      0003   000022 E3
    0003 R 000002 FM       0003   000003 FN       0003 R 000005 FNC      0003 R 000004 FNCBR    0000   000026 INJP$
    0003   000000 THETAB   0003   000001 THETAS   0004 R 000000 U        0003   000006 V        0000 R 000000 Y
    0003   000017 Y1       0003 R 000020 Y2       0000 R 000002 Z


00101       1*             SUBROUTINE MIXDER(DTBDX,DTBDY,DTFDY,D2TBXY,D2TFXY,DNCDX,DNCDY,
00101       2*            1                  D2TBXE,DA1DX,DA1DY,DA2DX,DA2DY,DA3DX,DA3DY,
00101       3*            2                  DA4DY,DA5DX,DA5DY,DA6DX,DA6DY,DLDX,DLDY,
00101       4*            3                  D2LDXY,DEBDY,DEBDX,DEX,DEY,DEPX,DEPY,DMDX,
00101       5*            4                  DMDY,D2MNCX,D2MNCY,B,C,D3TXYE,DTFDXY)
00101       6*      C
00101       7*      C      FOR MIXED DERIVATIVES OF U AND V      SET B=1. AND C= 0.
00101       8*      C      FOR MIXED DERIVATIVES OF U AND FNCBR SET B=1. AND C= 1.
00101       9*      C      FOR MIXED DERIVATIVES OF V AND FNCBR SET B=0. AND C= 1.
00101      10*      C
00103      11*             DIMENSION Y(2)
00104      12*             COMMON /BLKI/THETAB,THETAS,FM,FN,FNCBR,FNC,V,DNCDT1,DFNX,D2NDLL,
00104      13*            1          DFMX,DFM,D2MLNC,D2MDNC,D2FMLL,Y1,Y2,DE4DTB,E3,DE1DL/
00104      14*            2      BLKD/U,D3M2LN,D3M2NL,A1,A2,A3,A4,A5,A6,EB
00105      15*             Y(2)     = Y2
00106      16*             Z        = FNC
```


177945

```
00107              DTFDXY  = U*(D2TBXY-D2TFXY)+B*(DTBDY-DTFDY)
00110              D2A1XY  = 2*DA1DX*DA1DY/A1-A1**2*(D2TFXY-D2TBXY)
00111              D2A6XY  = 6*FNCBR*DTBDX*DTBDY+6*Y(2)*FNCBR*D2TBXY+C*6*Y(2)*DTBDX
00112              D3M2NY  = DLDY*D3M2NL
00113              DNCDXY  = 6*FNCBR*Y(2)*DTBDX*DTBDY+3*FNCBR*(Y(2)**2)*D2TBXY+
00113             I          C*3*(Y(2)**2)*DTBDX
00114              D3MNLY  = DLDY*D3M2LN+DNCDY*D3M2NL
00115              D3MNXY  = D3MNLY*DLDX+D2MLNC*D2LDXY+D3M2NY*DNCDX+D2MDNC*DNCDXY
00116              D2EXY   = DDETA(Z)*DNCDX*DNCDY+DETA(Z)*DNCDXY
00117              D2EPXY  = DDDETA(Z)*DNCDX*DNCDY+DDETA(Z)*DNCDXY
00120              D2MDLY  = DLDY*D2FMLL+DNCDY*D2MLNC
00121              D2MDXY  = DLDX*D2MDLY+DFMX*D2LDXY+D2MNCY*DNCDX+DFM*DNCDXY
00122              D2A5XY  = FM*D2EPXY+DEPX*DMDY+DEPY*DMDX+DETA(Z)*D2MDXY+DEY*D2MNCX+
00122             I          ETA(Z)*D3MNXY+DEX*D2MNCY+DFM*D2EXY
00123              D2NDXY  = DFNX*D2LDXY+DLDX*DLDY*D2NDLL
00124              D2EBXY  = FM*D2EXY+DMDY*DEX+ETA(Z)*D2MDXY+DEY*DMDX+D2NDXY
00125              D2A2XY  = -(DEBDY*DA2DX+DEBDX*DA2DY+A2*D2EBXY-(A6*D2A5XY+
00125             I          DA6DY*DA5DX+DA5DY*DA6DX+A5*D2A6XY))/EB
00126              D2A3XY  = DA3DX*DA3DY/A3+D2TBXY*DA3DX/DTBDX+
00126             I          A3*DTBDX*(-3*DTBDY/Y(2)**2-DA3DY)
00127              D2A4XY  = D2A1XY+D2A2XY+D2A3XY
00130              D3TXYE  = U*D2A4XY/A4**2-DA4DY*(2*A4*D2TBXE+B)/A4**2
00131              RETURN
00132              END

      END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS ETA
FOR S9A-07/27/72-19:38:27 (,0)

   FUNCTION ETA          ENTRY POINT 000036

   STORAGE USED: CODE(1) 000044; DATA(0) 000022; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   POLY
    0004   EXP
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000016 1L        0000 R 000001 A         0000 R 000010 B         0000 R 000000 ETA        0000    000014 INJP$
    0003 R 000000 POLY


00101       1*          FUNCTION ETA(X)
00103       2*          DIMENSION A(7), B(2)
00104       3*          DATA A(1),A(2),A(3),A(4),A(5),A(6),A(7)/0.10E+01, -0.1163143E+01,
00104       4*         1     0.1478836E+01, -0.1267550E+01, 0.6325223E+00, -0.1627067E+00,
00104       5*         2     0.1654223E-01/ B(1),B(2)/0.6866095E+00, -0.2297718E+00/
00116       6*          IF(X.GT.2.5) GO TO 1
00120       7*          ETA   = POLY(7,A,X)
00121       8*          RETURN
00122       9*        1 ETA   = B(1)*EXP(B(2)*X)
00123      10*          RETURN
00124      11*          END

      END OF COMPILATION:         NO  DIAGNOSTICS.
```

177947

```
@FOR,IS DETA
FOR S9A-07/27/72-19:38:44 (,0)

   FUNCTION DETA        ENTRY POINT 000036

   STORAGE USED: CODE(1) 000044; DATA(0) 000021; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   POLY
    0004   EXP
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000016 1L        0000 R 000001 A          0000 R 000007 B          0000 R 000000 DETA       0000     000013 INJP$
    0003 R 000000 POLY


00101        1*           FUNCTION DETA(X)
00103        2*           DIMENSION A(6), B(2)
00104        3*           DATA A(1),A(2),A(3),A(4),A(5),A(6)/-0.1163143E+01, 0.2957672E+01,
00104        4*         1      -0.3802650E+01, 0.2530089E+01, -0.8135335E+00, 0.9925338E-01/
00104        5*         2      B(1),B(2)/-0.1577635E+00, -0.2297718E+00/
00115        6*           IF(X.GT.2.5) GO TO 1
00117        7*           DETA  = POLY(6,A,X)
00120        8*           RETURN
00121        9*         1 DETA  = B(1)*EXP(B(2)*X)
00122       10*           RETURN
00123       11*           END

      END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS DDETA
FOR S9A-07/27/72-19:39:00 (,0)

      FUNCTION DDETA        ENTRY POINT 000036

      STORAGE USED: CODE(1) 000044; DATA(0) 000020; BLANK COMMON(2) 000000

      EXTERNAL REFERENCES (BLOCK, NAME)

       0003    POLY
       0004    EXP
       0005    NERR3$

      STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

       0001    000016 1L         0000 R 000001 A          0000 R 000006 B          0000 R 000000 DDETA      0000    000012 INJP$
       0003 R 000000 POLY


 00101                      FUNCTION  DDETA(X)
 00103                      DIMENSION  A(5), B(2)
 00104                      DATA  A(1),A(2),A(3),A(4),A(5)/0.2957672E+01, -0.7605300E+01,
 00104                    1       0.7590267E+01, -0.3254134E+01, 0.4962669E+00/ B(1),B(2)/
 00104                    2       0.3624960E-01, -0.2297718E+00/
 00114                      IF(X.GT.2.5) GO TO 1
 00116                      DDETA  = POLY(5,A,X)
 00117                      RETURN
 00120                    1 DDETA  = B(1)*EXP(B(2)*X)
 00121                      RETURN
 00122                      END

        END OF COMPILATION:         NO  DIAGNOSTICS.
```

177949

```
@FOR,IS DDDETA
FOR S9A-07/27/72-19:39:17 (,0)

    FUNCTION DDDETA       ENTRY POINT 000036

    STORAGE USED: CODE(1) 000044; DATA(0) 000017; BLANK COMMON(2) 000000

    EXTERNAL REFERENCES (BLOCK, NAME)

     0003   POLY
     0004   EXP
     0005   NERR3$

    STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

     0001   000016 1L         0000 R 000001 A          0000 R 000005 B          0000 R 000000 DDDETA     0000    000011 INJP$
     0003 R 000000 POLY


00101       1*           FUNCTION  DDDETA(X)
00103       2*           DIMENSION  A(4), B(2)
00104       3*           DATA  A(1),A(2),A(3),A(4)/-0.7605300E+01,0.1518053E+02,
00104       4*          1-0.9762402E+01,0.1985068E+01/
00104       5*          2 B(1),B(2)/-0.8329136E-02,-0.2297718E+00/
00113       6*           IF(X.GT.2.5) GO TO 1
00115       7*           DDDETA  = POLY(4,A,X)
00116       8*           RETURN
00117       9*         1 DDDETA  = B(1)*EXP(B(2)*X)
00120      10*           RETURN
00121      11*           END

       END OF COMPILATION:         NO  DIAGNOSTICS.
```

```
@FOR,IS POLY
FOR S9A-07/27/72-19:39:21 (,0)

   FUNCTION POLY         ENTRY POINT 000036

   STORAGE USED: CODE(1) 000044; DATA(0) 000015; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000012 1076G      0000   000003 INJP$     0000 I 000002 K          0000 I 000001 L          0000 R 000000 POLY


 00101       1*            FUNCTION POLY(N,A,X)
 00103       2*            DIMENSION A(N)
 00104       3*            POLY = 0.
 00105       4*            L = N
 00106       5*            DO 1 K=1,N
 00111       6*            POLY = POLY*X+A(L)
 00112       7*          1 L = L-1
 00114       8*            RETURN
 00115       9*            END

      END OF COMPILATION:       NO  DIAGNOSTICS.
```

177951

```
@FOR,IS SORV
FOR S9A-07/27/72-19:39:24 (,0)

     SUBROUTINE SORV       ENTRY POINT 000601

     STORAGE USED: CODE(1) 000605; DATA(0) 000066; BLANK COMMON(2) 000000

      COMMON BLOCKS:

      0003    BLKI    000024
      0004    BLKD    000012
      0005    BLKR    000012
      0006    VAB     000003

     EXTERNAL REFERENCES (BLOCK, NAME)

      0007    ETA
      0010    NCDERV
      0011    MDER
      0012    DETA
      0013    DERV
      0014    MIXDER
      0015    NERR3$

     STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

      0000 R 000003 AA       0004   000003 A1       0004   000004 A2       0004   000005 A3       0004   000006 A4
      0004   000007 A5       0004   000010 A6       0000 R 000005 BBB      0000 R 000037 DA1DN    0000 R 000007 DA1DU
      0000 R 000023 DA1DV    0000 R 000040 DA2DN    0000 R 000010 DA2DU    0000 R 000024 DA2DV    0000 R 000041 DA3DN
      0000 R 000011 DA3DU    0000 R 000025 DA3DV    0000 R 000042 DA4DN    0000 R 000012 DA4DU    0000 R 000026 DA4DV
      0000 R 000043 DA5DN    0000 R 000013 DA5DU    0000 R 000027 DA5DV    0000 R 000044 DA6DN    0000 R 000014 DA6DU
      0000 R 000030 DA6DV    0000 R 000045 DEBDN    0000 R 000004 DEBDTB   0000 R 000015 DEBDU    0000 R 000031 DEBDV
      0000 R 000046 DEN      0000 R 000047 DEPN     0000 R 000017 DEPU     0000 R 000033 DEPV     0012 R 000000 DETA
      0000 R 000016 DEU      0000 R 000032 DEV      0003   000023 DE1DL    0003   000021 DE4DTB   0003 R 000013 DFM
      0003 R 000012 DFMX     0003   000010 DFNX     0005 R 000006 DLDNCB   0005 R 000001 DLDU     0005 R 000002 DLDV
      0000 R 000050 DMDN     0000 R 000020 DMDU     0000 R 000034 DMDV     0000 R 000036 DNCDN    0003 R 000007 DNCDT1
      0000 R 000006 DNCDU    0000 R 000022 DNCDV    0000 R 000001 D2CD2T   0000 R 000002 D2CTNB   0003 R 000016 D2FMLL
      0005 R 000003 D2LDUU   0005 R 000004 D2LDUV   0005 R 000005 D2LDVV   0005 R 000007 D2LNCB   0005 R 000010 D2LUNB
      0005 R 000011 D2LVNB   0003 R 000015 D2MDNC   0003 R 000014 D2MLNC   0000 R 000051 D2MNCN   0000 R 000021 D2MNCU
      0000 R 000035 D2MNCV   0003   000011 D2NDLL   0004 R 000001 D3M2LN   0004 R 000002 D3M2NL   0004 R 000011 EB
      0006 R 000002 ET       0007 R 000000 ETA      0003   000022 E3       0003 R 000002 FM       0003 R 000003 FN
      0003 R 000005 FNC      0003 R 000004 FNCBR    0000   000056 INJP$    0005 R 000000 RLAM     0003 R 000000 THETAB
      0000 R 000000 THETAF   0003 R 000001 THETAS   0004 R 000000 U        0003   000006 V        0003 R 000017 Y1
      0003 R 000020 Y2       0006 R 000000 Z1       0006 R 000001 Z2


 00101      1*                 SUBROUTINE SORV(Y,DY,X)
 00103      2*                 DIMENSION Y(20),DY(20)
 00104      3*                 COMMON /BLKI/THETAB,THETAS,FM,FN,FNCBR,FNC,V,DNCDT1,DFNX,D2NDLL,
 00104      4*         1            DFMX,DFM,D2MLNC,D2MDNC,D2FMLL,Y1,Y2,DE4DTB,E3,DE1DL/
 00104      5*         2          BLKD/U,D3M2LN,D3M2NL,A1,A2,A3,A4,A5,A6,EB
```

```
00104              3        /BLKR/RLAM,DLDU,DLDV,D2LDUU,D2LDUV,D2LDVV,DLDNCB,
00104              4           D2LNCB,D2LUNB,D2LVNB
00104              5        /VAB/ Z1,Z2,ET
00105               Z1      = FNC
00106               Z2      = FM*ETA(FNC)+FN
00107               ET      = ETA(FNC)
00110               THETAF  = Y(1)
00111               THETAB  = Y(2)
00112               Y1      = Y(1)
00113               Y2      = Y(2)
00114               CALL NCDERV(FNCBR,THETAB,FNC,DNCDT1,D2CD2T,D2CTNB)
00115               CALL MDER(RLAM,FNC,FM,DFMX,DFM,D2FMLL,D2MDNC,D2MLNC,D3M2LN,D3M2NL)
00116               AAA     = THETAF-THETAB
00117               DY(1)   = -U*AAA
00120               EB      = FM*ETA(FNC)+FN
00121               DEBDTB  = 3*THETAB**2*FNCBR*(FM*DETA(FNC)+ETA(FNC)*DFM)
00122               BBB     = 4*THETAB**3/(THETAB**4-THETAS**4)
00123               DY(2)   = -U/(1/AAA+DEBDTB/EB+BBB)
00124               CALL DERV(Y(3),Y(4),Y(5),Y(6),DLDU,D2LDUU,DY(3),DY(4),DY(5),
00124              1         DY(6),0.,1.,DNCDU,DA1DU,DA2DU,DA3DU,DA4DU,DA5DU,
00124              2         DA6DU,DEBDU,DEU,DEPU,DMDU,D2MNCU)
00125               CALL DERV(Y(7),Y(8),Y(9),Y(10),DLDV,D2LDVV,DY(7),DY(8),DY(9),
00125              1         DY(10),0.,0.,DNCDV,DA1DV,DA2DV,DA3DV,DA4DV,DA5DV,
00125              2         DA6DV,DEBDV,DEV,DEPV,DMDV,D2MNCV)
00126               CALL DERV(Y(11),Y(12),Y(13),Y(14),DLDNCB,D2LNCB,DY(11),DY(12),
00126              1         DY(13),DY(14),1.,0.,DNCDN,DA1DN,DA2DN,DA3DN,DA4DN,
00126              2         DA5DN,DA6DN,DEBDN,DEN,DEPN,DMDN,D2MNCN)
00127               CALL MIXDER(Y(4),Y(8),Y(7),Y(16),Y(15),DNCDU,DNCDV,DY(4),DA1DU,
00127              1            DA1DV,DA2DU,DA2DV,DA3DU,DA3DV,DA4DV,DA5DU,DA5DV,
00127              2            DA6DU,DA6DV,DLDU,DLDV,D2LDUV,DEBDV,DEBDU,DEU,DEV,
00127              3            DEPU,DEPV,DMDU,DMDV,D2MNCU,D2MNCV,1.,0.,DY(16),
00127              4            DY(15))
00130               CALL MIXDER(Y(4),Y(12),Y(11),Y(18),Y(17),DNCDU,DNCDN,DY(4),
00130              1            DA1DU,DA1DN,DA2DU,DA2DN,DA3DU,DA3DN,DA4DN,DA5DU,
00130              2            DA5DN,DA6DU,DA6DN,DLDU,DLDNCB,D2LUNB,DEBDN,DEBDU,
00130              3            DEU,DEN,DEPU,DEPN,DMDU,DMDN,D2MNCU,D2MNCN,1.,1.,
00130              4            DY(18),DY(17))
00131               CALL MIXDER(Y(8),Y(12),Y(11),Y(20),Y(19),DNCDV,DNCDN,DY(8),
00131              1            DA1DV,DA1DN,DA2DV,DA2DN,DA3DV,DA3DN,DA4DN,DA5DV,
00131              2            DA5DN,DA6DV,DA6DN,DLDV,DLDNCB,D2LVNB,DEBDN,DEBDV,
00131              3            DEV,DEN,DEPV,DEPN,DMDV,DMDN,D2MNCV,D2MNCN,0.,1.,
00131              4            DY(20),DY(19))
00132               RETURN
00133               END

        END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS SCNTL
FOR S9A-07/27/72-19:40:52 (,0)

    SUBROUTINE SCNTL      ENTRY POINT 000147

    STORAGE USED: CODE(1) 000174; DATA(0) 000014; BLANK COMMON(2) 000000

     COMMON BLOCKS:

     0003    MCT     000005
     0004    VAB     000003
     0005    BLKI    000024

    EXTERNAL REFERENCES (BLOCK, NAME)

     0006    NWDU$
     0007    NI02$
     0010    NERR3$

    STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

     0000     000002 2000F      0001    000054 5L        0001    000061 50L       0001    000135 60L       0003 R 000000 DLMT
     0000 R 000000 DXSTR       0003 R 000003 DXWRT      0004 R 000002 ET        0003 I 000001 ICNT      0000    000006 INJP$
     0003 I 000001 LCNT        0003 I 000004 LSTEP      0005 R 000000 VAL       0003 R 000002 XWRT      0004 R 000000 Z1
     0004 R 000001 Z2


 00101       1*           SUBROUTINE SCNTL(Y,DY,DX,X,NTRY,IFVD)
 00103       2*           DIMENSION Y(20),DY(20)
 00104       3*           COMMON /MCT/ DLMT,ICNT,XWRT,DXWRT,LSTEP
 00104       4*          1        /VAB/ Z1,Z2,ET
 00104       5*          2        /BLKI/VAL(20)
 00105       6*           ICNT     = ICNT+1
 00106       7*           IF(DX.GE.DXWRT.AND.ICNT.GT.1) LSTEP = 1
 00110       8*           IF(ABS(X-XWRT).LT.DLMT) GO TO 50
 00112       9*           IF(XWRT.GT.X) GO TO 5
 00112      10*     C
 00114      11*           DXSTR    = DX
 00115      12*           DX       = DX+XWRT-X
 00116      13*           LCNT     = 1
 00117      14*           NTRY     = 3
 00120      15*           RETURN
 00120      16*     C
 00121      17*         5 NTRY     = 1
 00122      18*           RETURN
 00122      19*     C
 00123      20*        50  WRITE(6,2000) Y(1),Y(2),Z1,Z2,ET,VAL(3),VAL(4),X
 00135      21*      2000 FORMAT (8F15.7)
 00136      22*           IF(LCNT.EQ.1) DX = DXSTR
 00140      23*           LCNT     = 0
 00141      24*           IF(ABS(1.0-XWRT).LE.DLMT) GO TO 60
```

```
00143      25*           XWRT     = XWRT+DXWRT
00144      26*           NTRY     = 1
00145      27*           IF(LSTEP.EQ.0) RETURN
00147      28*           DX       = DXWRT
00150      29*           IFVD     = 1
00151      30*           RETURN
00151      31*      C
00152      32*        60 NTRY     = 2
00153      33*           RETURN
00154      34*           END

      END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS RKS
FOR S9A-07/27/72-19:41:32 (,0)

      SUBROUTINE RKS       ENTRY POINT 000643

      STORAGE USED: CODE(1) 001040; DATA(0) 000064; BLANK COMMON(2) 000000

      EXTERNAL REFERENCES (BLOCK, NAME)

       0003   NERR2$
       0004   NEXP5$
       0005   NERR3$

      STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

       0001   000010 10L      0001   000313 110L     0001   000333 120L     0001   000045 126G     0001   000343 130L
       0001   000071 140G     0001   000355 140L     0001   000105 146G     0001   000130 156G     0001   000417 160L
       0001   000150 164G     0001   000177 174G     0001   000500 185L     0001   000510 190L     0001   000013 20L
       0001   000232 205G     0001   000270 217G     0001   000524 220L     0001   000530 230L     0001   000543 240L
       0001   000374 243G     0001   000032 25L      0001   000552 250L     0001   000554 251L     0001   000572 257L
       0001   000604 259L     0001   000623 270L     0001   000456 300L     0001   000615 336G     0001   000054 40L
       0001   000060 45L      0001   000006 5L       0001   000076 50L      0001   000123 70L      0001   000135 80L
       0000 R 000014 AM       0000 R 000007 AMAX     0000 R 000011 C        0000 R 000010 D        0000 R 000001 DDT
       0000 R 000003 DELT     0000 R 000012 E        0000 R 000000 FR10     0000 I 000004 I        0000 I 000005 IFLAG
       0000   000030 INJP$    0000 I 000002 ISYMP    0000 I 000013 J        0000 R 000006 S


00101      1*        SUBROUTINE RKS(DERIV,CNTRL,Y,DY,A,R,T,DEL,N,IFVD,IBKP,NTRY,
00101      2*       1IERR,DELY,PD,SD,YS,YST,DYST,YSIMP)                              DG000200
00103      3*        DIMENSION Y(N),DY(N),A(N),R(N),DELY(N),                          DG0  3
00103      4*       1PD(N),SD(N),YS(N),DYST(N),YST(N),YSIMP(N)                       DG00040
00104      5*        EXTERNAL  DERIV, CNTRL                                          DG000500
00104      6*     C  FR10 IS  FIFTH ROOT OF TEN                                      DG00 60
00105      7*        FR10=1.5848932                                                  DG000700
00106      8*        IERR=0                                                          DG000800
00106      9*     C    YS  CONTAINS Y VALUES AT LEFT END POINT OF INTEGRATION INTERVAL DG00090
00106     10*     C                                                                  DG001000
00106     11*     C    YSIMP CONTAINS Y FOR SIMPSONS RULE CHECK  CHECK NOT MADE FOR  #G001100
00106     12*     C        FIXED STEP MODE    ISYMP IS CONTROL PARAMETER =1,FIXED,2 VARDG00120
00106     13*     C                                                                  DG001300
00106     14*     C    IF FIXED STEP SIZE GO ONE INTERVAL OF LENGTH DELT AND RETURN TO DG00140
00106     15*     C       CNTRL, IF VAR GO TWO INTERVALS BEFORE RETURN TO CONTRL     DG00150
00106     16*     C                                                                  DG001600
00106     17*     C    IFVD   = 0     VARIABLE INTERVAL                              DG00170
00106     18*     C           = 1     FIXED                                          DG001800
00106     19*     C    IBKP   = 0     CUT INTERVAL ONCE BEFORE REPEAT  (UNDER IFVD=0 ) DG00190
00106     20*     C           = 1     CUT AS REQUIRED                                DG0 200
00106     21*     C    NTRY   = 1     CONTINUE INTEGRATING                           DG002100
00106     22*     C             2     RETURN FROM RKS                                DG0 220
00106     23*     C             3     STEP REPEATED WITH NEW DELT                    DG002300
00106     24*     C             4     RESTART                                        DG00240
```

```
00106   C        IERR  = 0    NORMAL                                        DG002500
00106   C             =1    DELT=0, RETURN FROM RKS                         DG002600
00106   C              1    A(I)+ R(I)*ABS(Y(I)) = 0. , RETURN FROM RKS     DG002700
00107         5  IF(DEL) 20,10,20                                           DG002800
00112         10 IERR=-1                                                    DG002900
00113            GO TO 270                                                  D7003000
00114         20 CALL DERIV(Y,DY,T)                                         DG003100
00115            NTRY=1                                                     DG003200
00116            CALL CNTRL(Y,DY,DEL,T,NTRY,IFVD)                           DG003300
00117         25 DDT=DEL                                                    DG003400
00120            IF(IFVD) 40,30,40                                          DG003500
00123         30 ISYMP=2                                                    DG003600
00124            DELT=DEL/2.                                                DG00370
00125            DO 31 I=I,N                                                D7003800
00130         31 SD(I)=0.0                                                  DG00390
00132            IFLAG=1                                                    DG00400
00133            S=1.                                                       DG004100
00134            GO TO 45                                                   DG004200
00135         40 ISYMP=1                                                    DG004300
00136            DELT=DEL                                                   DG00440
00137         45 DO 46 I=1,N                                                DG004500
00142            YST(I)=Y(I)                                                DG00460
00143         46 DYST(I)=DY(I)                                              DG0 470
00145         50 DO 60 I=1,N                                                DG004800
00150            DELY(I)=DELT*DY(I)                                         DG004900
00151            PD(I)=DELY(I)                                              DG00500
00152         60 CONTINUE                                                   DG005100
00154            GO TO (80,70),ISYMP                                        DG005200
00155         70 DO 71 I=1,N                                                DG005300
00160         71 SD(I)=SD(I)+S*DY(I)                                        DG005400
00162         80 T=T+DELT/2.                                                DG005500
00163            DO 85 I=1,N                                                DG005600
00166            YS(I)=Y(I)                                                 DG00570
00167            Y(I)=YS(I)+DELY(I)/2.                                      DG005800
00170         85 CONTINUE                                                   DG005900
00172            CALL DERIV(Y,DY,T)                                         DG006000
00173            DO 90 I=1,N                                                DG006100
00176            DELY(I)=DELT*DY(I)                                         DG00620
00177            PD(I)=PD(I)+2.*DELY(I)                                     DG006300
00200            Y(I)=YS(I)+DELY(I)/2.                                      DG00640
00201         90 CONTINUE                                                   DG006500
00203            CALL DERIV(Y,DY,T)                                         DG006600
00204            DO 95 I=1,N                                                DG00670
00207            DELY(I)=DELT*DY(I)                                         DG00680
00210            PD(I)=PD(I)+2.*DELY(I)                                     DG006900
00211            Y(I)=YS(I)+DELY(I)                                         DG00700
00212         95 CONTINUE                                                   DG007100
00214            T=T+DELT/2.                                                DG007200
00215            CALL DERIV(Y,DY,T)                                         DG00730
00216            DO 100 I=I,N                                               DG007400
00221            DELY(I)=DELT*DY(I)                                         DG007500
00222            PD(I)=PD(I)+DELY(I)                                        DG00760
00223            Y(I)=YS(I)+PD(I)/6.                                        DG00770
00224        100 CONTINUE                                                   DG007800
00226            GO TO (110,120),ISYMP                                      DG007900
00227        110 NTRY=1                                                     DG008000
00230            CALL DERIV(Y,DY,T)                                         DG008100
```

177957

```
00231          CALL CNTRL(Y,DY,DEL,T,NTRY,IFVD)                DG00820
00232          GO TO 300                                        DG008300
00233      120 GO TO (130,140),IFLAG                            DG008400
00234      130 S=4.                                             DG008500
00235          IFLAG=2                                          DG008600
00236          CALL DERIV(Y,DY,T)                               DG008700
00237          GO TO 50                                         D7008800
00240      140 CALL DERIV(Y,DY,T)                               DG008900
00241          AMAX =0.0                                        DG009000
00242          DO 180 I=1,N                                     DG009100
00245          SD(I)=SD(I)+DY(I)                                DG009200
00246          YSIMP(I)=YST(I)+DELT*SD(I)/3.                    DG009300
00247          D   =ABS(Y(I)-YSIMP(I))                          DG00940
00250          C   =A(I)+R(I)*ABS(Y(I))                         DG009500
00251          IF(C   ) 160,150,160                             DG00960
00254      150 IERR=1                                           DG009700
00255          GO TO 270                                        DG009800
00256      160 E   =ABS(D   /C   )                              DG009900
00257          AMAX=AMAX1(AMAX,E)                               DG01000
00260      180 CONTINUE                                         D7010100
00262          IF(AMAX-1.) 215,215,230                          DG01020
00265      215 NTRY= 1                                          DG010300
00266          CALL CNTRL(Y,DY,DEL,T,NTRY,IFVD)                 DG010400
00267      300 IF(NTRY-1) 185,185,310                           DG01050
00272      310 IF(NTRY-2) 270,270,330                           DG01060
00275      330 IF(NTRY-3) 340,340,5                             DG01070
00300      340 T=T-DDT                                          DG01080
00301          IF(DEL) 259,10,259                               DG010900
00304      185 GO TO (40,190),ISYMP                             DG01100
00305      190 IF(AMAX-.75) 200,25,220                          DG011100
00310      200 IF(AMAX-.075) 210,25,25                          DG01120
00313      210 DEL=DEL*FR10                                     DG011300
00314          GO TO 25                                         DG011400
00315      220 DEL=DEL/FR10                                     DG011500
00316          GO TO 25                                         DG011600
00317      230 I =1+ IBKP                                       DG011700
00320          GO TO (240,250),I                                DG011800
00321      240 T=T-DEL                                          DG011900
00322          DEL=DEL/FR10                                     DG012000
00323          GO TO  259                                       DG01210
00324      250 J=1                                              DG012200
00325      251 AM=AMAX/10.**J                                   DG012300
00326          IF(1.-AM) 255,257,257                            DG01240
00331      255 J=J+1                                            DG012500
00332          GO TO 251                                        DG01260
00333      257 T=T-DEL                                          DG01270
00334          DEL=DEL/(FR10**J)                                DG01280
00335      259 DO 245 I=1,N                                     DG01290
00340          DY(I)=DYST(I)                                    DG013000
00341      245 Y(I)=YST(I)                                      DG013100
00343          GO TO 25                                         DG013200
00344      270 RETURN                                           DG013300
00345          END                                              DG013400

     END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,IS FMINV
FOR S9A-07/27/72-19:41:58 (,0)

   SUBROUTINE FMINV     ENTRY POINT 000254

   STORAGE USED: CODE(1) 000306; DATA(0) 001260; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000046 105G      0001   000151 11L       0001   000051 111G      0001   000071 117G      0001   000104 123G
    0001   000125 133G      0001   000130 137G      0001   000172 150G      0001   000175 154G      0001   000227 164G
    0001   000212 20L       0000 R 001214 AA        0000 R 001217 B         0000 I 001212 I         0000   001224 INJP$
    0000 I 001215 I1        0000 I 001220 I2        0000 I 001213 J         0000 I 001216 K         0000 R 000000 XMAT
```

```
 00101            SUBROUTINE FMINV (A,X,N,M)
 00103            DIMENSION A(N,N),X(N),XMAT(25,26)
 00104            DO 1 I=1,N
 00107            XMAT(I,M) = X(I)
 00110            DO 1 J=1,N
 00113          1 XMAT(I,J) = A(I,J)
 00116            DO 20 I=1,N
 00121            AA = XMAT(I,I)
 00122            DO 5 J=1,M
 00125          5 XMAT(I,J) = XMAT(I,J)/AA
 00127            IF (I.EQ.1) GO TO 11
 00131            I1 = I-1
 00132            DO 10 K=1,I1
 00135            B = XMAT(K,I)
 00136            DO 10 J=1,M
 00141         10 XMAT(K,J) = XMAT(K,J) - XMAT(I,J) * B
 00144            IF (I.EQ.N) GO TO 20
 00146         11 I2 = I+1
 00147            DO 15 K=I2,N
 00152            B = XMAT(K,I)
 00153            DO 15 J=1,M
 00156         15 XMAT(K,J) = XMAT(K,J) - XMAT(I,J) * B
 00161         20 CONTINUE
 00163            DO 25 I=1,N
 00166         25 X(I) = XMAT(I,M)
 00170            RETURN
 00171            END

      END OF COMPILATION:        NO  DIAGNOSTICS.
```

177959

```
@FOR,IS NCDERV
FOR S9A-07/27/72-19:42:07 (,0)

   SUBROUTINE NCDERV    ENTRY POINT 000031

   STORAGE USED: CODE(1) 000044; DATA(0) 000013; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000004 1DJPS      0000 R 000000 T2        0000 R 000001 T3


00101      1*           SUBROUTINE NCDERV(FNCBR,THETAB,FNC,DNCDT1,D2CD2T,D2CTNB)
00101      2*      C
00101      3*      C    NC AND ITS DERIVATIVES
00101      4*      C
00103      5*           T2      = THETAB**2
00104      6*           T3      = T2*THETAB
00105      7*           FNC     = FNCBR*T3
00106      8*           DNCDT1  = 3.*FNCBR*T2
00107      9*           D2CD2T  = 6.*FNCBR*THETAB
00110     10*           D2CTNB  = 3.*T2
00111     11*           RETURN
00112     12*           END

      END OF COMPILATION:        NO  DIAGNOSTICS.
```

QXQT
MAP 0023-07/27-19:42

177961

ADDRESS LIMITS 001000 021317 040000 047773
STARTING ADDRESS 020253
WORDS DECIMAL 8400 IBANK 4092 DBANK

SEGMENT MAIN		001000 021317		040000 047773
NSWTC$/FOR	1	001000 001021		
NRBLK$/FOR	1	001022 001044		
NRWND$/FOR	1	001045 001124	2	040000 040011
NWEF$/FOR	1	001125 001326	2	040012 040031
NFTCH$/FOR	1	001327 001617	2	040032 040067
NBDCV$/FOR	1	001620 001752	2	040070 040125
NFTV$/FOR	1	001753 001775		
NCLOS$/FOR	1	001776 002144	2	040126 040157
NWBLK$/FOR	1	002145 002266		
NBSBL$/FOR	1	002267 002323		
NUPDA$/FOR	1	002324 002356		
NBF00$/FOR			2	040160 042361
NCNVT$/FOR	1	002357 002603	2	042362 042451
NININ$/FOR	1	002604 003014	2	042452 042463
NOTIN$/FOR	1	003015 003330	2	042464 042467
NOUT$/FOR	1	003331 004317	2	042470 042514
NFMT$/FOR	1	004320 005176	2	042515 042571
NIOER$/FOR	1	005177 005351	2	042572 042676
NFCHK$/FOR	1	005352 006233	2	042677 043035
			4	043036 043107
NTAB$/FOR			2	043110 043146
ERU$/MISC				
NLINP$/FOR	1	006234 007747	2	043147 043330
TIR$/TECH	1	007750 010434	0	043331 043361
			2	043362 043641
NEXP6$/FOR	1	010435 010631	2	043642 043713
ASINCOS$/FOR	1	010632 011046	0	043714 043741
SQRT$/FOR	1	011047 011107	2	043742 043753
EXP$/FOR	1	011110 011177	2	043754 043774
NIER$/FOR	1	011200 011261	2	043775 044130
NOBJF$/FOR	1	011262 011326		
NEXP5$/FOR	1	011327 011414	2	044131 044140
NERR$/FOR	1	011415 011741	2	044141 044304
BLKR (COMMON BLOCK)				044305 044316
BLKD (COMMON BLOCK)				044317 044330
BLKI (COMMON BLOCK)				044331 044354
VAB (COMMON BLOCK)				044355 044357
MCT (COMMON BLOCK)				044360 044364
BLANK$COMMON (COMMON BLOCK)				

NCDERV	1	011742 012005	0	044365 044377
			2	BLANK$COMMON
FMINV	1	012006 012313	0	044400 045657
			2	BLANK$COMMON
RKS	1	012314 013353	0	045660 045743
			2	BLANK$COMMON
SCNTL	1	013354 013547	0	045744 045757
	3	MCT	2	BLANK$COMMON
	5	BLKI	4	VAB
SORV	1	013550 014354	0	045760 046045
	3	BLKI	2	BLANK$COMMON
	5	BLKR	4	BLKD
			6	VAB
POLY	1	014355 014420	0	046046 046062
			2	BLANK$COMMON
DDDETA	1	014421 014464	0	046063 046101
			2	BLANK$COMMON
DDETA	1	014465 014530	0	046102 046121
			2	BLANK$COMMON
DETA	1	014531 014574	0	046122 046142
			2	BLANK$COMMON
ETA	1	014575 014640	0	046143 046164
			2	BLANK$COMMON
MIXDER	1	014641 015314	0	046165 046270
	3	BLKI	2	BLANK$COMMON
			4	BLKD
INTMIX	1	015315 015346	0	046271 046277
	3	BLKI	2	BLANK$COMMON
DERV	1	015347 016267	0	046300 046427
	3	BLKI	2	BLANK$COMMON
			4	BLKD
INTIAL	1	016270 017011	0	046430 046552
	3	BLKI	2	BLANK$COMMON
MDER	1	017012 017315	0	046553 046640
			2	BLANK$COMMON
NDERV	1	017316 017405	0	046641 046655
			2	BLANK$COMMON
BNDCND	1	017406 017614	0	046656 046704
			2	BLANK$COMMON
CONST	1	017615 020262	0	046705 046775
			2	BLANK$COMMON
MAIN	1	020263 021317	0	046776 047773
	3	BLKI	2	BLANK$COMMON
	5	MCT	4	BLKD
			6	BLKR

SYS$*RLIB$. LEVEL 63
END OF COLLECTION - TIME 1.955 SECONDS

E-25-609

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering
Atlanta, Georgia

Final Report
Pt. 2

SPACE RADIATOR SIMULATION

MANUAL FOR COMPUTER CODE

Contract No. NAS 9-10415

by
William Z. Black and Wolfgang Wulff

Sponsored by the
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Houston, Texas

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Stothe P. Kezios, ~~Ph.D.~~
Director, School of Mechanical Engineering

FOREWORD

This report constitutes the Users Manual that accompanies the computer simulation of a space radiator system. It summarizes a two year project carried out by the School of Mechanical Engineering at the Georgia Institute of Technology, Atlanta, Georgia for the NASA Manned Spacecraft Center, Houston, Texas under Contract No. NAS 9-10415. The results of the analysis phase of the program are contained in a separate report entitled "Space Radiator Simulation - System Analysis". A third report submitted under this contract covers the development of a simplified system simulation and the initial phases of a system optimization procedure.

The contract was entitled "Study of Design Parameters of Space Base and Space Shuttle Heat Rejection Systems". The work was monitored by Dr. W. E. Simon of the Power Generation Branch of NASA MSC, Houston, Texas, and was carried out by Dr. W. Z. Black and Dr. W. Wulff as Co-Investigators and Mr. S. M. Morcos, Mr. S. L. Yao and Mr. R. M. Hinson graduate students in the School of Mechanical Engineering under the direction of Dr. S. P. Kezios. Mr. C. R. Caldarale of the Rich Electronic Computing Center also contributed to this report.

The Work carried out by Dr. W. Z. Black is reflected in Section B.2 a and b and Section B.3, d through f, of the Permanent Part of the program. The program units of the Selective part described in Section B.3 were completed by Mr. Morcos under the direction of the Co-Investigators.

Dr. Black is responsible for the coding of programs No. 14 through 22, for the supervision of coding programs No. 23 through 30 which was carried out by Mr. Caldarale and Mr. Hinson and for the supervision of coding programs No. 51 through 60 which was carried out by Mr. Morcos. Dr. W. Wulff is responsible for the general program structure described in Section B.1 and the program units described in the Sections B.3a through c and B.3g of the Permanent Part of the program. Dr. Wulff coded programs 1 through 7, 31 through 38 and 40 through 42 and supervised Mr. Yao in the coding of programs No. 8 through 13 and No. 39 and supervised Mr. Morcos in the coding of programs No. 43 through 50 and No. 61 and 62.

SUMMARY

This manual describes a computer program that simulates the performance of a space radiator. The program basically consists of a rigorous analysis which analyzes a symmetrical fin panel and an approximate analysis that predicts system characteristics for cases of non-symmetrical operation. The rigorous analysis accounts for both transient and steady state performance including aerodynamic and radiant heating of the radiator system. The approximate analysis considers only steady state operation with no aerodynamic heating.

The first section of this manual contains a description of the radiator system and instructions to the user for program operation. The input required for the execution of all program options is described. Several examples of program output are contained in this section. Sample output includes the radiator performance during ascent, reentry and orbit.

The second section of the user's manual describes the structure of the entire program as well as the function of each program unit. All interfaces between the various program units are described so that the user may remove a single unit or group of program units that have general utility for use in other analyses. This section concludes with a program listing.

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LIST OF FIGURES

A. USERS INSTRUCTIONS

1. Program Objectives and Capabilities

The program units described in this manual constitute a transient heat transfer analysis of a space radiatior heat rejection system. The analysis is intended to simulate the radiator system of the space base and the space shuttle for conditions of arbitrarily prescribed combinations of aerodynamic heating and incident solar, earth albedo and planetary irradiation.

An exact analysis is performed for the radiator system consisting of equally spaced parallel coolant channels existing in one plane connected by plane fin panels of trapezoidal cross-section. The midplane between tubes and a parallel plane passing through the tube axis are assumed to be planes of symmetry for the purpose of the exact analysis. The program results are extended over the entire radiator panel on the basis of this symmetry.

An approximate analysis is used to extend the exact program simulation to cover the situation of the non-symmetrical radiator panel. This extension predicts on the assumption of one-dimensional analysis, the system performance when the radiator panel is curved and when the tubes are unequally spaced, non-symmetrically loaded or U-shaped.

The exact system analysis predicts both transient and steady-state, two-dimensional temperature profiles, local and total heat transfer rates and coolant fluid temperature and pressure profiles in the flow channel. The analysis also predicts the protection layer thickness which covers the coolant channel and the inlet and exit manifold tubing. Total system mass and projected area are calculated.

The program units described in this manual serve to simulate the radiator system performance. Even though successive runs with system parameter variations are feasible, the task of system optimization is dealt with in the simplified analysis which is described in detail in the Simplified Analysis Manual.

The purpose of this manual is to describe the program units that make up the computer simulation, the necessary input parameters for program execution and the typical program output for simulated radiator operation. The deck composition is described in part 2, and the input data set is explained in part 3. Part 4 is devoted to a description of the program output and part 5 gives examples of typical radiator performance for ascent, reentry and orbital conditions. Section B describes each subprogram in detail by describing their input and output variables as well as the function of each program unit.

The simulation program is separated into modular units or subprograms so that units of general utility may be removed and run separately. This arrangement also facilitates program modifications if future changes are required. The subprogram concept also reduces the extent of program checking when new program units are added to the existing program package.

The entire program consists of 62 separate program units and the Data Set. The source language is FORTRAN V. The program is executed from catalogued files, using temporary data files as batch processing on the UNIVAC 1108 computer operating under EXEC 8, Version 27.20.143, at the Georgia Tech Rich Electronic Computer Center.

Except for the control statements necessary to collect the program into elements to be stored on mass storage for subsequent program execution from mass storage, the Executive Control Statements are not discussed. Control statements may be freely chosen by the user in accordance with the Executive Control Language. All statements are in 026 key punch code.

a. System Description

The exact simulation program predicts the performance characteristics of the typical coolant channel and fin segment shown in Fig. 1. The fin profile has a trapezoidal cross-sectional area. The parallel plane passing through the tube axis and the plane bisecting two adjacent tubes are assumed to be planes of symmetry.

The program has property options that allow the user to select from a number of different coolant fluids, structural and meteoroid protection materials and surface coatings. The materials available for the protection layer, tube and fin are beryllium, copper or aluminum in any combination. The coolant fluids may be selected from a gas, several liquids or a liquid metal.

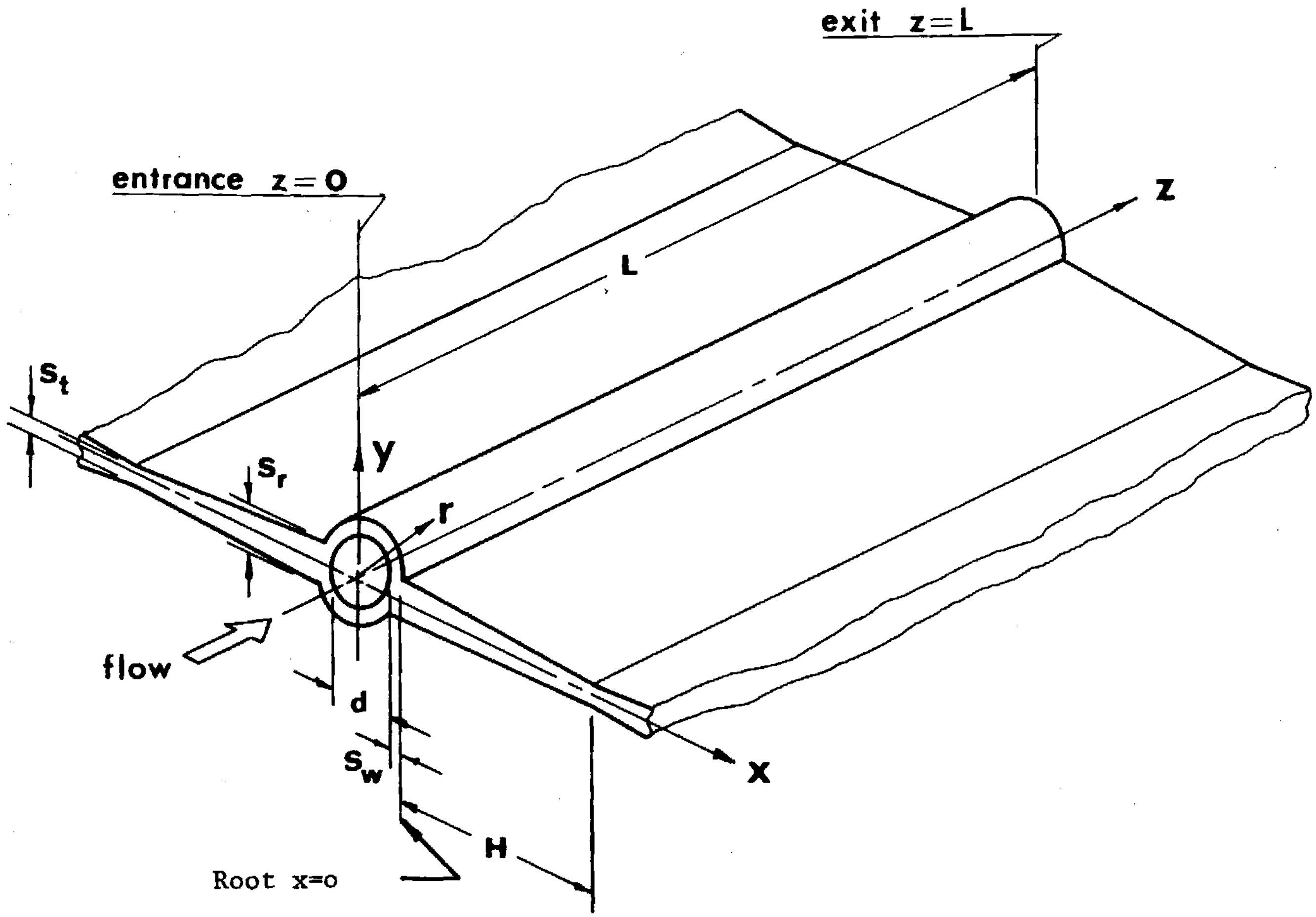


Fig. 1 Typical Fin Element for Exact Analysis

Possible choices are helium, silicon oil, the two fluorochemicals FC-43 and FC-75 and the liquid metal NaK. The entire radiator system is covered with the same passive thermal coating Z-93 which has optically diffuse but wavelength and temperature dependent optical properties.

The approximate analysis predicts the performance of the non-symmetrical radiator panels shown in Fig. 2. This one-dimensional analysis predicts the approximate location of the adiabatic plane separating two adjacent coolant channels when the radiator panel is curved (Fig. 2a) or the coolant channels are shaped in form of the letter U (Fig. 2b). Other situations which the approximate analysis is capable of treating involve the radiator panel with non-uniformly spaced coolant channels and coolant channels that do not all have identical inlet fluid mass flow rates or identical inlet fluid temperatures.

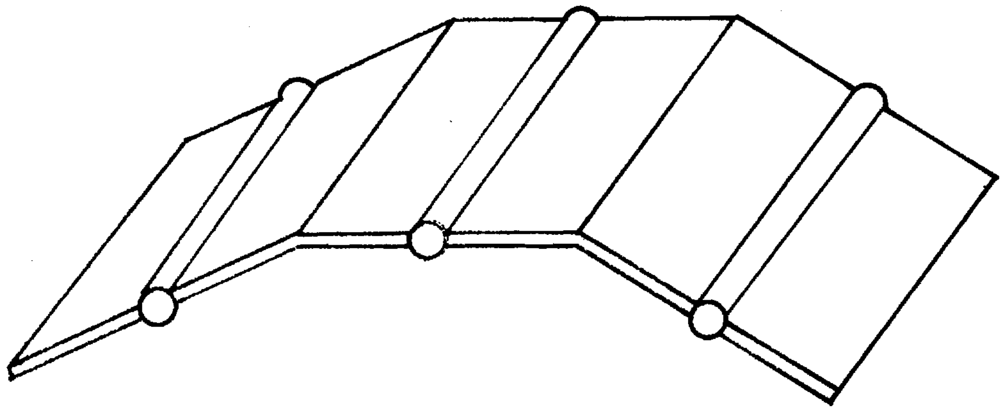
b. Operating Conditions

The program simulates radiator characteristics for ascent and reentry of the shuttle radiator system as well as orbital conditions for the shuttle and space base radiator. Typical system performance for these conditions are shown in part 5 of this manual.

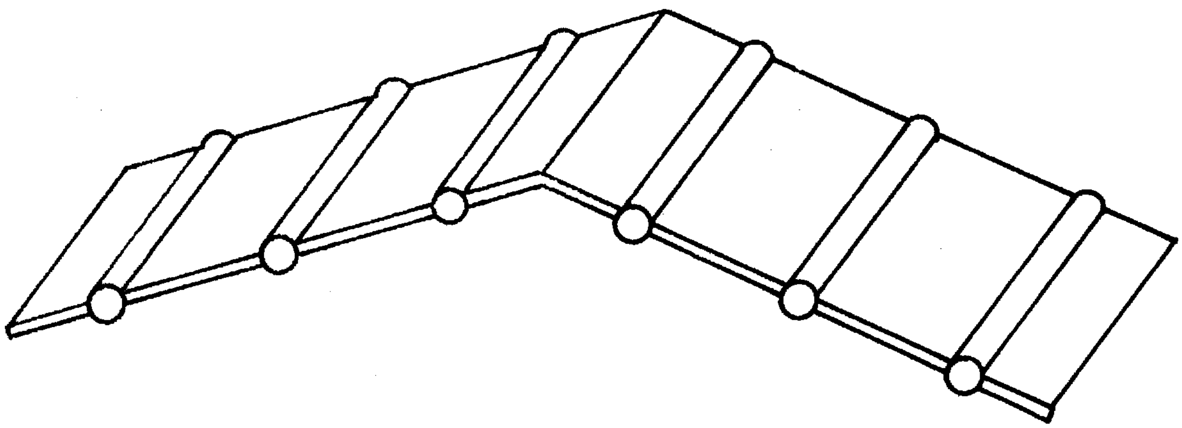
The altitude and velocity profiles of the shuttle vehicle during ascent and reentry are supplied by the user. These profiles are read into the program from card images.

The irradiation data to be supplied by the user is subdivided into three basic categories: solar, earth albedo and planetary irradiation. This data may be either read from card images or from a previously prepared data file which contains the irradiation data in the format specified by the MRI radiant flux program.

The program is capable of system simulation for both transient and steady state conditions. Under the steady state option, integration of the system differential equations proceeds from the user supplied initial condition until steady state is reached. All environmental conditions such as incident radiant flux remain constant during the integration process. Under the transient option, the environmental conditions are allowed to change with time as the integration process proceeds.



(a) Curved Radiator Panel



(b) U Shaped Coolant Channels

Fig. 2 Radiator Panel For Approximate Analysis

Provision has been made within the program to allow for the variation in coolant fluid temperature and mass flow at the inlet plane of the coolant channel. These variations must be supplied by the user as sets of discrete data values punched on cards.

2. The Deck Composition

The program structure is dictated by the calling sequence of the Runge-Kutta-Simpson integration procedure (see Section III-2 of the System Analysis Manual). The Source Deck consists of two parts. The first part, referred to as the Permanent Part, requires no attention from the user unless he plans major program modifications, for instance to accommodate geometrical configurations other than the one considered here. The Permanent Part contains the first 42 program units.

The second part, called the Selective Part, is assembled from case to case by the user in accordance with his choice of the

(i) coolant fluid
(ii) flow channel material
(iii) meteoroid protection layer material
(iv) fin panel material
(v) thermal control coating

There are always 20 program units in the Selective Part.

Following the Source Deck is the Data Set which is discussed in Section A-3. It consists of six groups, one for each of the following input specifications:

(i) parameters which specify non-symmetrical radiator panel
(ii) ascent and reentry profiles
(iii) solar, albedo and planetary irradiation
(iv) coolant fluid inlet temperature and mass flux histories
(v) system specifications
(vi) program options.

Most of the user's activities will be reflected in his manipulation of the Data Set, especially of the data in groups (v) and (vi) above.

3. The Input Data Set

Input data are divided into six groups and assembled in the order of increasing frequency of changes so that data records most likely to be changed are at the end of the Data Set. This enables the user to keep large portions of the Job Deck on mass storage. The six groups in the Data Set define

(i) the parameters which specify the non-symmetrical radiator panel
(ii) the ascent and reentry profiles
(iii) the incident thermal radiant flux as a function of time
(iv) the coolant fluid inlet temperature and mass flux histories
(v) the system specifications, other than material selections
(vi) the options of program execution.

The program may be executed successively after reading new data records beginning at any of the six data groups listed above. Provisons have been also made for restarting the program by reading new data records from one group and skipping the following data group or only skipping portions of the succeeding data groups. The restart options are determined by the value of the restart integer MRSTRT. A description of this integer is given in part (f) of this section.

None of the data groups contains a fixed number of records. The number of records in groups (ii), (iii) and (iv) are determined and specified to the computer by the user. Groups (i), (v) and (vi) contain a minimum of records as specified below; the number of additional records in these groups and of additional sets of groups (ii), (iii) and (iv) depend on the number of additional executions and parameter variations during the same job. In the description of data records (card images) the numbering starts from one in each group.

a) Alphabetical List of Input Data

All input variables needed for program operation are listed below with their units and a brief description of the meaning of the variable.

VARIABLE NAME	UNITS	REFERENCED IN	DESCRIPTION
ABEMF		FINA	ratio of solar absorptivity to infrared emissivity of coating material
AL	ft	TUBEA	array of tube lengths
ALIMIT		RUNØPT	absolute error limit per integration step
ALPHA	gm/(day ft^2)	PRØTLR	constant relating meteoroid flux to mass
ALTA	ft	ascent and reentry data	elements in altitude array used for ascent altitude profile of shuttle
ALTR	ft	ascent and reentry data	elements in altitude array used for reentry altitude profile of shuttle
AMAN	ft^2	MANIFD	total manifold area projected into plane of fin
AN		PROTLR	see equation 8.6 System Analysis Manual
ATK		PRØTLR	see equation 8.8 in System Analysis Manual
BTA		PRØTLR	constant relating meteoroid flux to mass
D	in	TUBEA	tube internal diameter
DITBI	in	TUBE	internal tube diameter
DTWRTE	hr	RUNØPT	fixed time interval between data printout
GAMMA		PRØTLR	constant used to adjust observed to predicted meteoroid penetration depth

H	in	FINA	array of fin heights
HFNI	in	FIN	fin height from root to tip
ICASE		QNML,MRI	integer value which specifies set of irradiation values on MRI file
ISYM		SYSTEM	integer which specifies type of non-symmetrical loading of tubes
ITAPE		QNML,MRI	integer value to specify card input (= 0) or MRI file input (≠ 0) for irradiation data
LFLD		RUNØPT	control integer used to select between variable or fixed inlet fluid properties
LIMWRT		RUNØPT	maximum number of data recordings during integration toward steady state
LTS		RUNØPT	control integer used to select initial system temperature
LTT		RUNØPT	control integer used to select between temperature dependent or independent surface coating properties
M	lbm/hr	FLUIDA	array of mass flow rates at inlets to tubes
MDØTI	lbm/hr	FLØW	total coolant mass flow rate
MRSTRT		GINPT	control integer used for selection of reentry point for restarting program
MSTØTR		RUNØPT	control integer for selecting transient or steady state computation
MZ		TUBE	number of nodal points along tube axis ($\leq$ 10)
NA		ascent and reentry data	number of instances for specified ascent velocity and altitude data
NCØNV		RUNØPT	control integer for selection of orbit, ascent or reentry

NFLD		inlet coolant fluid history	number of mass flow rate and temperature data values
NR		ascent and reentry data	number of instances for specified reentry velocity and altitude data
NRMP		PRØTLR	number of radial nodal points in the protection layer ($\leq$ 5)
NRTBI		TUBE	number of radial nodal points in tube wall ($\leq$ 5)
NSRD		SYSTEM	number of sides of the radiator panel which radiate (1 or 2)
NT		SYSTEM	number of flat symmetrically loaded panels
NTBS		TUBE	number of flow channels
NTM		QNML,MRI	number of instances for specified irradiation data (< 100)
NX		FIN	number of nodal points on fin perpendicular to flow channel ($\leq$ 10)
PHI		PROTLR	see equation 8.1 System Analysis Manual
PHIN	degrees	MRI	array of angles that relate fin panel orientation with MRI data
PHN	degrees	QNML	angle of panel relative to MRI data
PIN	lbf/ft^2	FLUIDA	array of pressures at inlet to tubes
PO	lbf/ft^2	FLØW	entrance pressure into flow channel
PRØB		PRØTLR	probability of no damage caused by meteoroid impact
RHØFNI	lbm/ft^3	FIN	fin material density
RHØMET	g/cm^3	PRØTLR	meteoroid density
RHØMPI	lbm/ft^3	PRØTLR	protection layer density

RHØTBI	lbm/ft^3	TUBE	tube wall density
RLIMIT		RUNØPT	relative error per integration step
SRØØTI	in	FIN	fin root thickness
STAGX	ft	FIN	distance from stagnation point on shuttle to center of radiator panel along a streamline
STBI	in	TUBE	tube wall thickness
STIPI	in	FIN	fin tip thickness
TA	sec	ascent and reentry data	elements in time array used for ascent velocity and elevation profiles
TAU	days	PRØTLR	time radiator is exposed to meteoroid environment
TEND	hr	RUNØPT	termination time for transient performance calculation
TH	in	FINA	array of fin thickness
THETA		PRØTLR	see equation 8.1 System Analysis Manual
TI	R	RUNØPT	initial system temperature
TIFLD	R	coolant fluid inlet temper-ature history	array of coolant fluid inlet temperatures
TIN	R	FLUIDA	array of temperatures at inlets to tubes
TO	R	FLØW	entrance temperature into flow channel
TØ	min	QNML,MRI	time in minutes at which irradiation data is required
TR	sec	ascent and reentry data	elements in time array used for reentry velocity and elevation profiles
TSTAR	R	SYSTEM	array of sink temperatures

VELA	ft/sec	ascent and reentry data	elements in velocity array used for ascent velocity profile of shuttle
VELM	ft/sec	PRØTLR	average meteoroid velocity
VELR	ft/sec	ascent and reentry data	elements in velocity array used for reentry velocity profile of shuttle
VERTX	ft	FIN	total dimension of radiator panel in direction parallel to acceleration of gravity
W1	in	TUBEA	array of distances between side segments of tubes when U-shaped
W2	in	TUBEA	array of distances between base segments of tubes when U-shaped
WIFLD	lbm/hr	coolant fluid inlet mass flow rate history	array of coolant fluid inlet mass flow rates
XL	ft	TUBE	tube length

b) Parameters Specifying Non-Symmetrical Radiator Panels

Normal program operation assumes that radiator conditions are symmetrical about each coolant fluid channel. Several factors may destroy this symmetry. One may be non-uniform spacing of the tubes. Another factor may be different inlet temperatures or mass flow rates into adjacent tubes. A third factor could be attributed to a curved panel resulting in a variation to sink temperature between adjacent fin segments. These factors are specified in the NAMELIST's that follow.

Numerical values for a non-symmetrical panel, for irradiation data and for system specifications are read into the computer in NAMELIST format, one NAMELIST each with name and input data as follows:

i) for non-symmetrical panel specifications (see Section (b))

- SYSTEM for selection of system parameters when panels and/or flow conditions are non-symmetrical
- TUBEA for non-symmetrical tube specifications
- FINA for non-symmetrical fin specifications
- FLUIDA for non-symmetrical fluid specifications
- MRI for non-symmetrical irradiation data

ii) for irradiation specifications (see Section (c))

- QNML for irradiation data under symmetrical radiator panel conditions

iii) for system specifications (see Section (f))

- TUBE for flow channel specifications
- FLØW for coolant fluid flow specifications
- FIN for fin parameter specifications
- PRØTLR for the protection layer specifications
- MANIFD for the manifold input data.

Each input data record under NAMELIST format has

(i) a blank in its first column,

(ii) a $ - sign in its second column,

(iii) the NAMELIST name, starting in the third column, followed by one or more blanks,

(iv) the string of data in free field format as follows:

A = b ,

where (A) is the variable name and (b) is a number; imbedded blanks between (A), (=), (b), (,) and a following (A) are permissible,

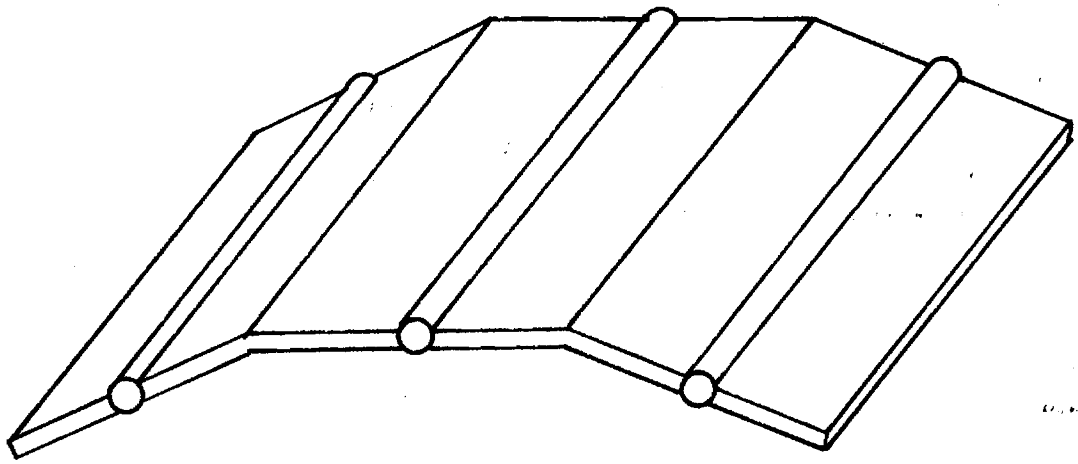
(v) the comma of the last datum is to be placed by a $ - sign which delimits the NAMELIST data string.

For more details concerning NAMELIST formating, the reader may consult standard texts on FORTRAN PROGRAMMING. The NAMELIST data strings must be sequenced in the order in which they are listed above.

i) <u>NAMELIST/SYSTEM/</u>contains 4 variables

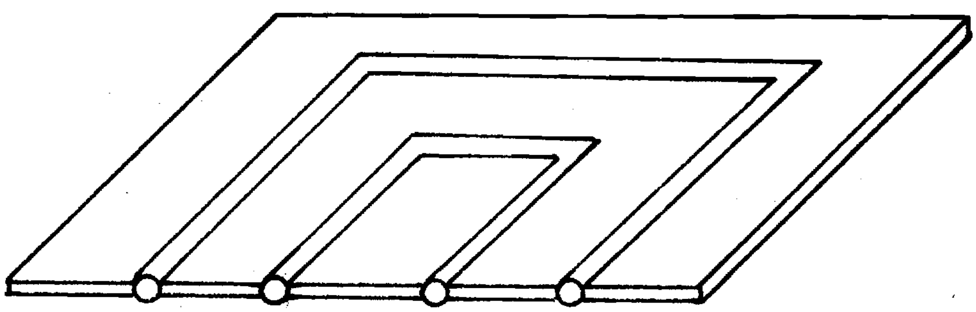
NT		number of flat symmetrically loaded panels, each panel containing NTBS symmetrically loaded tubes (see Fig. 3)
NSRD	= 1	for one side of the panel radiating
	= 2	for both sides of the panel radiating Note: if panel is curved NSRD is set equal to 1
ISYM	= 0	for symmetrical panel in one plane and straight parallel equally spaced tubes
	= 1	for non-symmetrical curved panel consisting of straight fin segments and straight parallel tubes
	= 2	for non-symmetrical panel in one plane with U-shaped tubes
	= 3	for non-symmetrical curved panel consisting of straight fin segments and U-shaped tubes
	= 4	for non-symmetrical panel in one plane with straight parallel tubes but non-symmetrical loading
TSTAR		an (NT,3) array of sink temperatures in °R. These values are ignored if MRI file is used for incident flux data (see Section (d)). Also: If the radiator panel is flat only (1, NSRD) of the array is required.

The following four NAMELIST's are not read and should not be placed in the program if ISYM = 0. If ISYM ≠ 0 these four NAMELIST's should appear in the order shown.



NT = 3

NTBS = 1



NT = 2

NTBS = 3

Fig. 3

Examples of the Input Parameters NT and NTBS

ii) NAMELIST/TUBEA/contains 4 variables

D	the single value of all tube internal diameters in inches
AL	an array of NT tube lengths in feet. These values are used only for straight tubes. For curved tubes, the lengths are calculated from the values of W1 and W2 which are read in below
W1	distance between U-shaped tubes along inlet and exit portion of the tube in inches (i.e., both side segments of the U) NT + 1 values
W2	distance between U-shaped tubes along bottom segment of U in inches, NT + 1 values (see Fig. 4 for details of dimensions W1 and W2)

iii) NAMELIST/FINA/contains 3 variables

H	NT + 1 values of the fin height in inches from tube centerline to midplane between tubes. This value is used on for the case of straight tubes. Fin height for cases of the U tube is calculated from W1 and W2 in NAMELIST TUBEA
TH	NT values for the fin thickness in inches
ABEMF	ratio of the solar absorptivity to infrared emissivity of the surface of the radiator system

iv) NAMELIST/FLUIDA/contains 3 variables

TIN	NT values for the inlet fluid temperatures in R
PIN	NT values for the inlet fluid pressure in lbf/ft^2
M	NT values for the inlet fluid mass flow rate in lbm/hr

v) NAMELIST/MRI/contains 5 variables

ITAPE	= 0	to read irradiation data from cards
	> 0	to read irradiation data from MRI file. Value of ITAPE designates the input unit used to read file data
ICASE		integer used to designate the case number of stored data to be used for input. ICASE = 3, for example, would designate the third set of data stored on the MRI file to be used for current input. If ITAPE = 0, this integer is ignored.

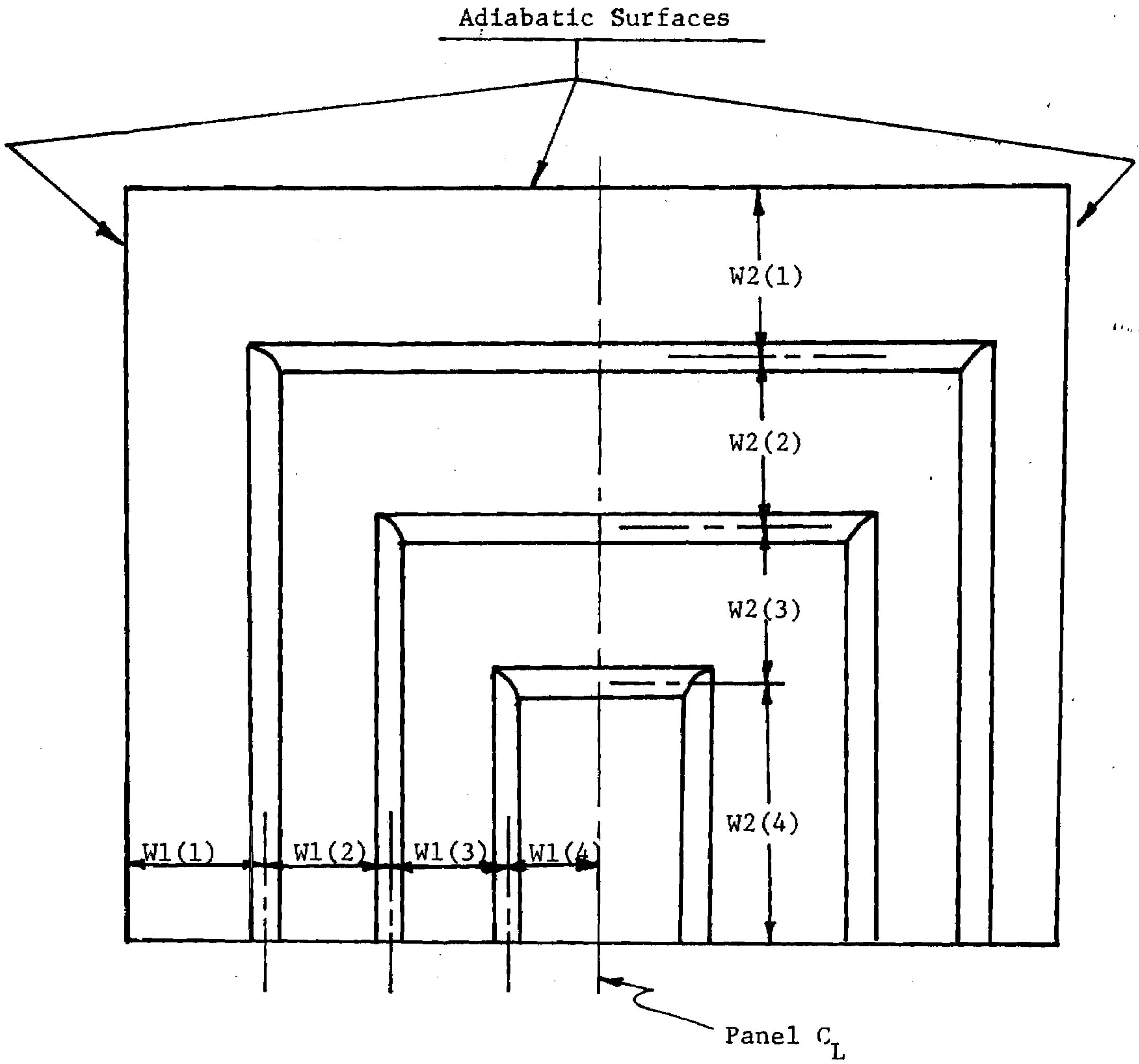


Fig. 4 The Dimensions W1(I) and W2(I)
for U Shaped Coolant Channels

NTM	number of instances at which incident flux values on to be specified if either card or file data is used; NTM $\leq$ 100. If ITAPE > 0, NTM must be the number of data values stored on the MRI file
TØ	time in minutes during orbit at which irradiation data is required. Time is measured from zero time specified on MRI output data. If ITAPE = 0 this value is ignored
PHIN	array of NT values of the angles in degrees between the normals to the NT flat radiator segments and the reference line used as the zero angle reference on the MRI program

c) Ascent and Reentry Data

Velocity and altitude profiles for the shuttle vehicle during both ascent and reentry are read from cards which have the format listed in the table below. Selection of ascent or reentry phases is determined by the control integer NCØNV (see Section (e) which explains the Execution Control Options).

Card No.	FØRMAT	Variable
1	2I10	NA,NR the number of ordered pairs of elements in the velocity-time and altitude-time arrays for ascent and reentry profiles, respectively
2 through INT* (NA/10 + 0.9) + 1 = N_1	10F8.3	TA, elements of time array (NA values) in seconds, selected for ascent velocity and elevation profiles
N_1+ 1 through N_1+ INT(NR/10+0.9) = N_2	10F8.3	TR, elements of time array (NR values) in seconds, selected for reentry velocity and elevation profiles

*INT(x) = Integer part of x

N_2+ 1 through N_2+ INT(NA/8+0.875) = N_3	8E10.3	VELA, elements of velocity array (NA values) in ft/sec, selected for ascent velocity profile of orbiter
N_3+ 1 through N_3+ INT(NR/8+0.875) = N_4	8E10.3	VELR, elements of velocity array (NR values) in ft/sec, selected for reentry velocity profile of orbiter
N_4+ 1 through N_4+ INT(NA/8+0.875) = N_5	8E10.3	ALTA, elements of altitude array (NA values) in ft, selected for ascent elevation profile of orbiter
N_5 + 1 through N_5+ INT(NR/8+0.875)	8E10.3	ALTR, elements of altitude array (NR values) in ft, selected for reentry elevation profile of orbiter

d) Irradiation Data

Incident radiant flux on the space base during orbit may be either read from card images or it may be read from a user supplied data file (MRI program). The selection of card or file input is determined by the value of the control integer ITAPE. If ITAPE = 0, the irradiation data is read from cards in the format shown below. If ITAPE > 0, the irradiation data is read from unit ITAPE. The data is assumed to be in the format specified in the MRI manual "Orbiting Satellite Surface Temperature Prediction and Analysis," MRI Project No. NAS9-1059.

The input variables used to input the irradiation data are to be supplied in the NAMELIST format called QNML, if ISYM = 0. The input strings must be in the sequence shown below. If ISYM ≠ 0, these values are supplied from the NAMELIST called MRI

NAMELIST/QNML/contains 5 variables

ITAPE = 0 to read irradiation data from cards

> 0 to read irradiation data from MRI tape. Value of ITAPE designates the input unit used to read file data

ICASE integer used to designate the case number of stored data to be used for input. ICASE = 3, for example, would designate the third set of data stored on the MRI file as the irradiation data to be used for current input. If ITAPE = 0, this integer is ignored

NTM	number of instances at which incident fluxes are to be specified if either card or file data is used; NTM $\leq$ 100. If ITAPE > 0, NTM must be the number of data values stored on the MRI file
TØ	time in minutes during orbit at which irradiation data is required. Time is measured from zero time specified on MRI output data. If ITAPE = 0 this value is ignored
PHN	single angle in degrees between normal to panel and reference line used as a zero angle reference in MRI program.

If the irradiation data is to be read from cards, it must be in the format shown below with the cards immediately following the NAMELIST input cards for QNML.

Card No.	FØRMAT	Variable
1 through NTM	10F8.3	On each card: (i) time TM in seconds (ii) 3 values of solar (iii) 3 values of albedo (iv) 3 values of planetary irradiation (Btu/hr ft^2) Incident at TM and each coming from one of three directions in this order: (i) -30° (ii) 0° (iii) +30° from the panel normal (upper side)
NTM + 1 through 2*NTM	10F8.3	Same data as above, now for lower fin panel side, only if NSRAD = 2

e) Coolant Fluid Temperature and Mass Flux Histories

When the temperature and mass flow rates entering the coolant channels vary with respect to time, the variation in these quantities are entered from cards in the format indicated below.

Card No.	FØRMAT	Variable
1	I10	NFLDTA the number of data values of temperature and mass flow rate to be entered on each card:
2 through NFLD + 1	3F20.6	i) TMEFLD the time in hours corresponding to the given temperature and mass flow rate ii) TIFLD coolant fluid temperature in R at time NFLDTA iii) WIFLD coolant mass flow rate in lbm/hr at time NFLDTA

f) System Specifications

The system specifications define the radiator system and follow immediately after the ascent and coolant fluid temperature and mass flux histories.

The first four cards in the group of the system specification data contain the names of

(i) the tube material
(ii) the fin material
(iii) the coolant fluid
(iv) the meteoroid protection layer material

in alphanumeric form, beginning with an alphabetic character. Each name is punched on a separate card, beginning in the first column and extending no further than through the first twelve columns. These names serve to identify the printout of results. The user must supply these names in agreement with the composition of the Selective Part described in Chapter I.A. The subsequent data records contain numerical data.

(i) NAMELIST/TUBE/contains 7 variables

DITBI	internal (hydraulic) tube diameter, in inch,
STBI	tube wall thickness, in inch,
XL	tube length, in ft,
RHØTBI	tube wall density, in lbm/ft^3,
MZ	number of nodal points along the tube axis (no. of intervals plus one), ≤ 10,
NRTBI	number of nodal points in radial direction, in the tube wall, ≤ 5,
NTBS	number of flow channels.

(ii) NAMELIST/FLOW/contains 3 variables

MDØTI	total coolant mass flow rate, in lbm/hr,
TO	entrance (and reference) temperature in degrees R,
PO	entrance (and reference) pressure in lbf/ft^2.

(iii) NAMELIST/FIN/contains 7 variables

NX	number of nodal points on the fin, perpendicular to the channel axis, NX ≤ 10,
SRØØTI	fin root thickness, in inch,
HFNI	fin height, from root to tip, in inch,
STIPI	fin tip thickness, in inch,
RHØFNI	fin material density, in lbm/ft^3,
STAGX	distance from stagnation point on shuttle vehicle to the center of radiator system measured along a streamline, in ft,
VERTX	total dimension of radiator panel in the direction parallel to the acceleration of gravity, in ft.

(iv) NAMELIST/PRØTLR/contains 13 variables

NRMP	number of radial nodal points in the protection layer, ≤ 5,
RHØMPI	protection layer material density, in lbm/ft^3,
RHØMET	meteoroid density in g/cm^3,
VELM	meteoroid velocity in ft/sec,
TAU	time that vulnerable area is exposed to meteoroid environment, in days,
PRØB	probability of no damage caused by meteoroid impacts, dimensionless,

ALPHA	experimental constant that relates meteoroid flux and mass (see Eq. 8.4) in gm/(day ft^2),
BTA	experimental constant that relates meteoroid flux and mass (see Eq. 8.4) dimensionless,
GAMMA	empirical constant used to adjust predicted penetration depths to one observed experimentally (see Eq. 8.1) dimensionless,
PHI	empirical constant (see Eq. 8.1) dimensionless,
THETA	empirical constant (see Eq. 8.1) dimensionless,
ATK	empirical constant used to account for spalling on a target of finite thickness (see Eq. 8.8) dimensionless,
AN	experimental constant that describes penetration depth as a function of angle of incidence (see Eq. 8.6) dimensionless.

(v) NAMELIST/MANIFD/contains

AMAN	total manifold area, projected into the fin plane, in ft^2.

Any one of these variables may be changed for successive program executions by entering them in NAMELIST/GINPT/ as discussed below.

g) Execution Control Options

The user has the choice of options for the execution of the first as well as successive computer runs.

Two data records are considered to be execution controls: RUNØPT and GINPT.

(vi) NAMELIST/RUNØPT/contains 11variables

MSTØTR = 1	to compute steady state conditions
= 2	to simulate transient system performance,
DTWRTE	fixed time interval, in hr, between data printout during integration,
TEND	termination time, in hr, for transient performance calculation,
ALIMIT	absolute error limit per integration step, see Eq. 15.3, in Systems Analysis Manual

RLIMIT		relative error limit per integration step, see Eq. 15.3, in Systems Analysis Manual.
TI		initial temperature, in degrees R,
LIMWRT		maximum number of data recording during integration toward steady state, exclusive of initial conditions record and steady state record,
NCØNV	= 0	no aerodynamic heating
	= 1	ascent
	= 2	reentry,
LTT	= 0	optical properties of the surface coating are independent of temperature
	= 1	optical properties of the surface coating are dependent on temperature
	= 2	irradiation on fin on tube is zero but subroutine QINCID is called,
LFLD	= 1	coolant fluid inlet temperature and mass flow rate are constant
	= 2	temperature and mass flow rate of inlet coolant fluid is variable,
LTS	= 0	uniform initial system temperature equal to TI
	= 1	initial system temperature taken to be equal to previously obtained values.

(vii) NAMELIST/GINPT/contains every variable name listed in items (i) through (vi) in addition to NSRD and the following control integer.

MRSTRT	= 1	new velocity and altitude profiles
	= 2	new irradiation history
	= 3	both new velocity, altitude profiles plus new irradiation history
	= 4	new coolant fluid inlet conditions
	= 5	new coolant fluid inlet conditions, plus new velocity and altitude profiles
	= 6	new coolant fluid inlet conditions, plus new irradiation history
	= 7	new coolant fluid inlet conditions, plus new velocity and altitude profiles, plus new irradiation history
	= 8	the only new input variables are those specified in GINPT.

There may be as many NAMELIST/GINPT/ records as computing time permits. If GINPT is omitted, the program will terminate.

4. Results

a. Information Produced

The results produced by the program can be divided into three categories each of which is listed on a separate output page. All input variables that specify the system and select the program options are printed on the first page of output (see Fig. 5). The second page contains all initial line conditions and system parameters which remain constant during the integration process (see Fig. 6). The succeeding pages contain the current system description printed during the integration process (see Fig.7). If the system is non-symmetrical an additional page of output is printed. This page (see Fig. 8) lists system parameters when the radiator panel is curved, the flow channels are not identically loaded, or the flow channels are U-shaped.

b. Output Format

The first output record consists of the list of all system specifications and execution control data as listed in Sections 3(d) and 3(e). This output appears with all of the variables in the NAMELISTS TUBE, FLØW, FIN, PRØTLR, MANIFD and RUNØPT listed in the NAMELIST format. A sample of this output is shown in Fig. 5 .

On the second page of output the initial coolant fluid flow properties are printed in non-dimensional form (see Fig. 6). This information includes non-dimensional pressure, velocity, temperature, and tube wall temperature. The reference quantities are listed below the initial line conditions. They are inlet fluid pressure, velocity and temperature. Next are printed several dimensionless parameters such as the Reynold's number, Prandtl number and Nusselt number for the initial coolant fluid flow conditions. The quantity DELTA is the ratio of the internal tube diameter to the tube length. The relative pressure is given by equation 3.31 in the System Analysis Manual. The Biot number of the tube is also printed.

```
@XQT N.VER1
 $TUBE
 DITBI    =     .25000000E+00
 STBI     =     .10000000E+00
 XL       =     .20000000E+01
 RHOTBI   =     .16859200E+03
 MZ       =                +5
 NRTBI    =                +3
 NTBS     =               +12

 $END
 $FLOW
 MDOTI    =     .50000000E+03
 TO       =     .70000000E+03
 PO       =     .25000000E+04

 $END
 $FIN
 NX       =                +5
 SROOTI   =     .50000000E-01
 HFNI     =     .12000000E+02
 STIPI    =     .50000000E-01
 RHOFNI   =     .16859200E+03
 STAGX    =     .20000000E+02
 VERTX    =     .10000000E+02

 $END
 $PROTLR
 NRMP     =                +3
 RHOMPI   =     .11357400E+03
 RHOMET   =     .50000000E+00
 VELM     =     .65600000E+05
 TAU      =     .36500000E+04
 PROB     =     .99000000E+00
 ALPHA    =     .18800000E-09
 BTA      =     .12130000E+01
 GAMMA    =     .15000000E+01
 PHI      =     .50000000E+00
 THETA    =     .66666700E+00
 ATK      =     .17500000E+01
 AN       =     .10000000E+01

 $END
 $MANIFD
 AMAN     =     .43000000E+02

 $END
 $RUNOPT
 MSTOTR   =                +2
 DTWRTE   =     .83330000E-02
 TEND     =     .20000000E+00
 ALIMIT   =     .50000000E-04
 RLIMIT   =     .10000000E-04
 TI       =     .66000000E+03
 LIMWRT   =               +20
 NCONV    =                +0
 LTT      =                +0
```

FIGURE 5

INPUT VARIABLES

```
LFLD     =          +2
LTS      =          +0
$END
```

INITIAL LINE CONDITIONS
******* **** **********
(ALL QUANTITIES ARE NORMALIZED)

PT.NO.	POSITION Z	PRESSURE P	VELOCITY W	FLUID TEMPERATURE T	WALL TEMPERATURE TWI
1	.000	1.000000	.974335	.942857	.942857
2	.250	.998340	.974339	.942857	.942857
3	.500	.996680	.974342	.942858	.942857
4	.750	.995020	.974346	.942858	.942857
5	1.000	.993359	.974350	.942858	.942857

INLET PRESSURE PO = 2500.000 LBF/SQ.FT
REF. VELOCITY WO = .69331 FT/SEC
REF. TEMPERATURE TOO = 700.000 R

REYNOLDS NO = .13191+03
PRANDTL NO = 95.079041
DELTA = .010417
REL.PRESSURE IS .170849+04

INIT. NUSSELT NO. NU = .768940+01
WALL BIOT NO. BI = .362036-02

SYSTEM PARAMETERS
****

TUBE LENGTH , XL = 2.000 FT
INTERNAL DIAMETER , DITB = .250 IN
WALL THICKNESS , STB = .100 IN
MATERIAL ALUMINUM
MASS (ALL TUBES) , MTB = 3.0896 LBM
NUMBER OF TUBES, NTBS = 12

FIN HEIGHT , HFN = 12.000 IN
THICKNESS AT ROOT , SROOT = .050 IN
THICKNESS AT TIP , STIP = .050 IN
MATERIAL ALUMINUM
MASS (ALL FINS) , MFN = 33.7184 LBM
NO. OF FIN SIDES RADIATING = 1

COOLANT FLUID IS SILICONE OIL
MASS (IN ALL TUBES) , MFL = 4.9345 LBM

PROTECTION LAYER THICKNESS, SMP = .063 IN
MASS, MMP = 1.804 LBM
MATERIAL IS BERYLLIUM

TOTAL MASS (EXCL. MANIFLD.) MTOT = 43.5462 LBM
TOTAL AREA (SINGLE NORMAL PROJECTION) ,
ATOT = 48.9000 SQ FT

FIGURE 6

INITIAL LINE CONDITIONS AND SYSTEM PARAMETERS

ELAPSED TIME IS .0000 HR
RELATIVE TIME IS .0000 **IN ORBIT** 1 INTEGR. STEPS

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 700.000 R
REF. RADIANT HEAT FLUX PER UNIT AXIAL LENGTH, QREF = .9877+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1295+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .0000 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.1295+05 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.6564	.9429	.9429	.9429	.9429	.9429
.250	.6552	.9429	.9429	.9429	.9429	.9429
.500	.6551	.9429	.9429	.9429	.9429	.9429
.750	.6552	.9429	.9429	.9429	.9429	.9429
1.000 (EXIT)	.6564	.9429	.9429	.9429	.9429	.9429

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 700.000 R
REFERENCE PRESSURE, P00 = 2500.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .693 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .433766+05 BTU/HR
EXIT CURRENTLY EI = .361473+05 BTU/HR
INLET CURRENTLY HI = .361472+05 BTU/HR
TOT. REJECTION DH = -.108887+00 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	.9743	.9429	.9429	.9429	-.000057	.00000
.250	.99834	.9743	.9429	.9429	.9429	.000283	.05725
.500	.99668	.9743	.9429	.9429	.9429	.000548	.25331
.750	.99502	.9743	.9429	.9429	.9429	.000803	.56830
1.000 (EXIT)	.99336	.9743	.9429	.9429	.9429	.001039	1.00000

FIGURE 7

CURRENT SYSTEM DESCRIPTION

ELAPSED TIME IS .0083 HR
RELATIVE TIME IS 10.3992 **IN ORBIT** 23 INTEGR. STEPS

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION

REFERENCE TEMPERATURE, T00 = 700.000 R
REF. RADIANT HEAT FLUX PER UNIT AXIAL LENGTH, QREF = .9877+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1198+05 BTU/HR
COND. FROM MANIFOLDS. CONDMF = .4641+03 BTU/HR

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.1085+05 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.6304	.9342	.9342	.9342	.9342	.9342
.250	.6024	.9332	.9248	.9233	.9232	.9233
.500	.6010	.9331	.9244	.9228	.9226	.9228
.750	.6022	.9331	.9248	.9233	.9232	.9233
1.000 (EXIT)	.6292	.9338	.9338	.9338	.9338	.9338

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER

REFERENCE TEMPERATURE, T00 = 700.000 R
REFERENCE PRESSURE, P00 = 2500.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .693 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .433766+05 BTU/HR
EXIT CURRENTLY EI = .378522+05 BTU/HR

INLET CURRENTLY HI = .385222+05 BTU/HR
TOT. REJECTION DH = .670021+03 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0046	.9539	.9342	.9342	25.000915	.00000
.250	.99824	1.0046	.9525	.9332	.9332	24.412890	.27294
.500	.99648	1.0046	.9512	.9331	.9331	22.919608	.53364
.750	.99473	1.0046	.9499	.9331	.9331	21.380966	.77689
1.000 (EXIT)	.99297	1.0046	.9488	.9338	.9338	18.983883	1.00000

FIGURE 7 CONCLUDED

FLAT PANEL
3 STRAIGHT TUBES
2 RADIATING SIDES

TUBE SPECIFICATIONS 2.5000-01 INCHES INSIDE DIAMETER

TUBE LENGTH (FEET)
2.0000+00 2.0000+00 2.0000+00

FIN SPECIFICATIONS

FIN THICKNESS (INCHES)
5.0000-02 5.0000-02 5.0000-02

FIN HALF-WIDTH (INCHES)
1.1000+01 1.1500+01 1.2000+01 1.2500+01

SINK TEMPERATURE (DEGREES R)
4.9391+02 4.9391+02 4.9391+02
5.8736+02 5.8736+02 5.8736+02

FLUID SPECIFICATIONS

INLET TEMPERATURE (DEGREES R)
7.0000+02 7.0000+02 7.0000+02

INLET PRESSURE (LBF/SQ.FT.)
2.5000+03 2.5000+03 2.5000+03

MASS FLOW RATE (LBM/HR)
5.0000+02 5.0000+02 5.0000+02

FIGURE 8

SYSTEM PARAMETERS FOR NON-SYMMETRICAL HEATING

TUBE	BULK TEMP DEG R	INCHES TO ADIABATIC PLANE LEFT	RIGHT	PER CENT FIN EFFICIENCY LEFT	RIGHT	FIN TIP TEMP DEG R LEFT	RIGHT	OUTLET TEMP DEG R	HEAT REJECTED BTU/HR
1	6.0619+02	1.1000+01	1.1531+01	5.9360+01	5.7589+01	5.7493+02	5.7314+02	6.0619+02	1.4465+03
2	6.0570+02	1.1469+01	1.2028+01	5.7816+01	5.6025+01	5.7314+02	5.7135+02	6.0570+02	1.4542+03
3	6.0524+02	1.1972+01	1.2500+01	5.6226+01	5.4593+01	5.7135+02	5.6975+02	6.0524+02	1.4613+03

A listing of system parameters follows the initial line condition. The system parameters include the pertinent geometry parameters, the materials and the mass of the tube, fin, coolant fluid and protection layer materials. In addition, the thickness of the meteoroid protection layer, the total system mass excluding the mass of the manifolds and the total projected areas are listed at the bottom of the page.

Following the preliminary results is a series of current system descriptions printed out during the integration process (see Fig. 7). The first items printed are the current real time and the relative time which is the ratio of the current time to the time required for a fluid particle to pass through the flow channel. If the calculations are for the space base in orbit, the words "in orbit" are printed at the top of the page. If the calculations are for either ascent or reentry of the space shuttle, the current shuttle velocity and altitude are printed along with the current atmospheric temperature. For either the sub-orbital or orbital case, the cummulative number of integration steps from the initial conditions is printed at the top of the page.

The next data printed are a summary of the heat flux terms and a listing of the non-dimensional fin temperature distribution. The reference temperature is the inlet fluid temperature and the reference radiant heat flux is the black body emissive power at the inlet coolant fluid temperature evaluated for a unit length of fin and tube segment. The total radiant rejection and the conduction into the fin from both the inlet and exit manifolds for the entire radiator system are also printed. The external heat fluxes incident on the system that are printed are the infrared irradiation from earth albedo, solar irradiation and the convective flux on the radiator system of the shuttle vehicle during ascent and reentry. The energy storage rate for the entire system is also listed along with the external heat fluxes.

The final table listed on the page contains coolant fluid properties as functions of axial distance as well as the local cooling rates. All properties are tabulated in non-dimensional form and the table is preceded by a list of the necessary reference quantities. Properties of the coolant fluid that are printed are pressure, velocity and bulk temperature. The non-dimensional interior tube wall temperature and the normalized temperature of the meteoroid protection layer temperature are also listed as functions of axial distance down the tube. The enthalpy rejection of the fluid and fraction of the total enthalpy drop are listed as functions down the tube. The latter parameter is helpful in determining the effectiveness of the various segments of the tube length in their capacity to reject heat. Below the reference properties used for the fluid properties are the inlet and exit fluid stagnation enthalpies as well as the total change in stagnation enthalpy. These quantities are labeled respectively, HI, HE and DH. Also for comparison is listed the enthalpy flux at the reference state (T_o,P_o) and the reference velocity W_o.

The last table of current output data constitutes either the system conditions at the specified termination time, TEND in hours, or the steady state condition depending on whether MSTØTR = 1 or MSTØTR = 2, respectively. For conditions of steady state, the words "STEADY STATE IS REACHED" are printed after the final data printout.

When input parameters lead to a condition for which the tube centerline or the midplane separating two tubes are not lines of symmetry, then a single page of output is printed prior to all other output. This page contains a written description of tube arrangement on the radiator and a printout describing the panel as either flat or curved. The number of non-symmetrical tubes and the number of sides of the panel radiating are also printed at the top of the page.

The next output consists of a description of the sink temperature data including orientation of the fin segments relative to the reference vector used in the MRI program.

The tube specifications follow the sink temperature data. The data listed are the internal tube diameter and the tube lengths when the tubes are straight. If the tubes are U-shaped, the spacings at the inlet and outlet segments as well as the crossover segments of the tubes are listed instead of the tube lengths.

The fin specifications follow the tube data. The data listed are fin thicknesses and the distance between the tube centerline and the midplane separating two tubes. The effective sink temperature for each fin segment is also printed under fin specifications. When both sides of the panel radiate, two lines of sink temperatures are printed corresponding to the sink temperature both radiator sides.

The coolant fluid specifications follow the fin data. Inlet fluid temperature, pressure and mass flow rates are printed for each non-symmetrical tube.

The final data to be printed on the page is a summary of the system conditions for all of the non-symmetrical fin segments. The data printed includes the fin bulk temperature, position of the adiabatic plane, the fin effectiveness, fin tip temperature, fluid outlet temperature and total heat rejected by the fluid in each of the tubes.

This single page of output is then followed by the usual system printout as described above, repeated once for each non-symmetrical tube.

c. Output Listing

Figures 5, 6 and 7 in this section are typical output listings produced by the simulation program. Figure 5 provides a listing of all input parameters that appear in the NAMELIST format. Figure 6 shows initial line conditions and system parameters and Figure 7 shows a typical printout of the current radiator system parameters. These three figures are typical of program output when the radiator panel is symmetrical about each flow channel. If non-symmetrical conditions exist, output similar to that shown in Figure 8 is produced.

5. Typical Radiator System Performance

This section summarizes typical program results for expected radiator input conditions during ascent and reentry for the shuttle vehicle and during both transient and steady state performance of the radiator system in a simulated orbit.

a. Ascent

(i) Mission Description

The ascent altitude and velocity profiles used for the system output shown in Figures 10 and 11 is given in Figure 9. Other input parameters were selected as reasonable conditions expected for a typical space shuttle radiator system. The total fin area of 124.5 ft^2 is subdivided by 10 equally spaced 12-foot long flow channels. The total fin height between flow channels is 1 ft. The inlet coolant fluid temperature and pressure are 200 F and 60 lb_f/in^2, respectively. The system materials are aluminum tubes, fins and meteoroid protection material with silicon oil as the coolant fluid. Other system parameters are printed as input listing which precedes the current system parameters shown in Figure 10a. The panel radiates only from one side. Incident radiant fluxes are constant during ascent at 100 Btu/hr ft^2 for solar irradiation, 2.0 Btu/hr ft^2 for earth albedo. There is no infrared earth irradiation.

(ii) System Response

The response of the radiator system during ascent is summarized in Figures 10 and 11. A selected number of output listings of current system parameters during ascent are shown in Figure 10a. Figure 10b is a plot of the total heat rejection from the entire radiator surface during ascent as well as the outlet coolant fluid temperature. Figure 11 is a plot of the aerodynamic heating at various times during the ascent phase of the mission.

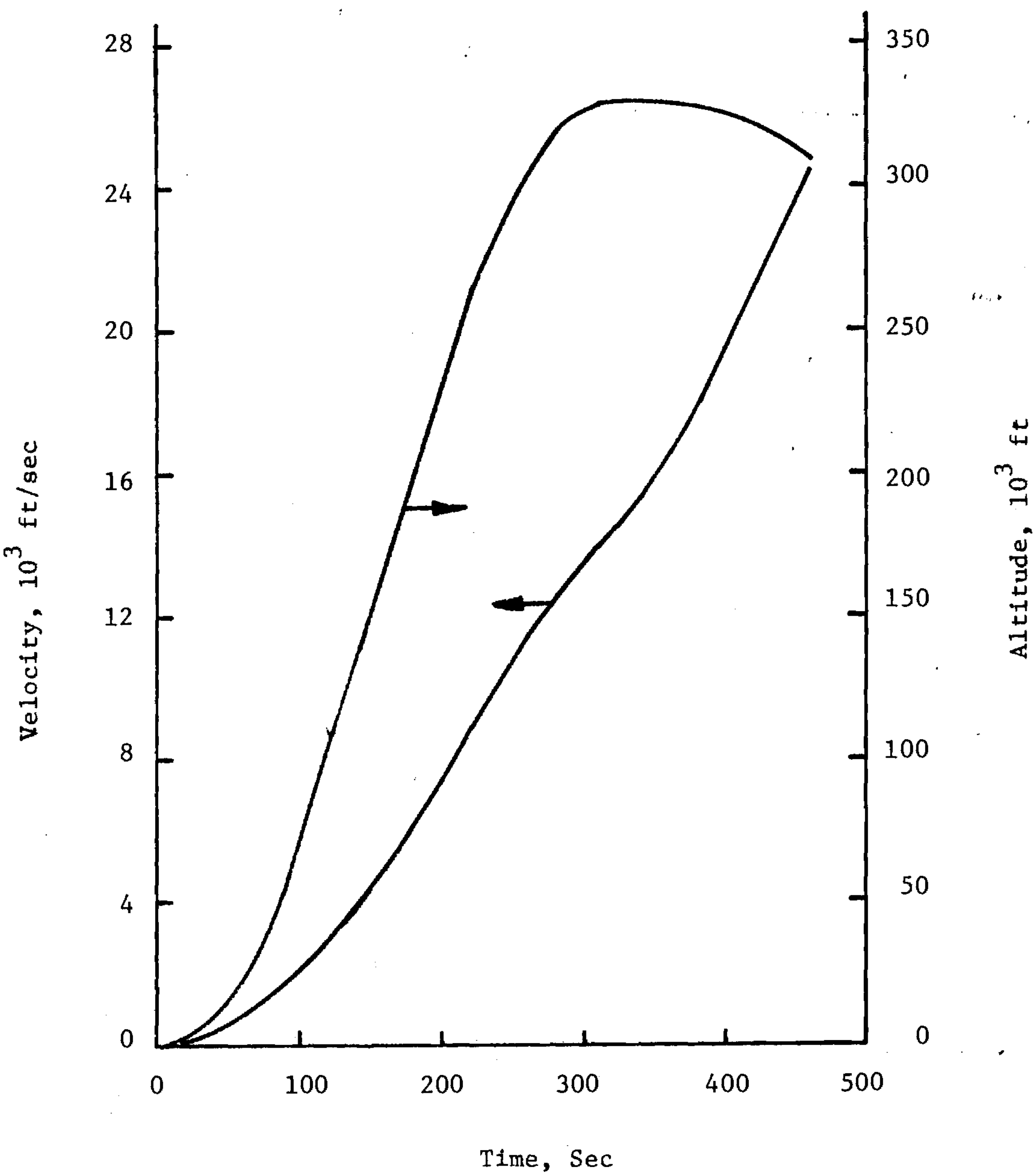


Fig. 9 Ascent Velocity and Altitude Profiles

```
$QNML
ITAPE   =                +0
ICASE   =                +0
NTM     =                +4
TO      =   .00000000E+00
PHN     =   .00000000E+00

$END
$TUBE
DITBI   =   .25000000E+00
STBI    =   .10000000E+00
XL      =   .12000000E+02
RHOTBI  =   .16859200E+03
NZ      =                +9
NRTBI   =                +3
NTBS    =               +10

$END
$FLOW
MDOTI   =   .50000000E+03
TO      =   .65967000E+03
PO      =   .86400000E+04

$END
$FIN
NX      =                +5
SROOTI  =   .50000000E-01
HFNI    =   .60000000E+01
STIPI   =   .50000000E-01
RHOFNI  =   .16859200E+03
STAGX   =   .20000000E+02
VERTX   =   .10000000E+02

$END
$PROTLR
NRPP    =                +3
RHOMPI  =   .16859200E+03
RHOMET  =   .50000000E+00
VELM    =   .65600000E+05
TAU     =   .36500000E+04
PROB    =   .99000000E+00
ALPHA   =   .18800000E-09
BTA     =   .12130000E+01
GAMMA   =   .15000000E+01
PHI     =   .50000000E+00
THETA   =   .66666700E+00
ATK     =   .17500000E+01
AN      =   .10000000E+01

$END
$MANIFD
AMAN    =   .43000000E+02

$END
$RUNOPT
MSTOTR  =                +2
```

FIGURE 10(A) SYSTEM RESPONSE FOR ASCENT PROGRAM OUTPUT

```
DTWRTE   =    .83330000E-02
TEND     =    .12700000E+00
ALIMIT   =    .50000000E-04
RLIMIT   =    .10000000E-04
TI       =    .65967000E+03
LIMWRT   =              +25
NCONV    =               +1
LTT      =               +0
LFLD     =               +1
LTS      =               +0

$END
```

FIGURE 10(A) CONTINUED

INITIAL LINE CONDITIONS
******* **** **********
(ALL QUANTITIES ARE NORMALIZED)

PT.NO.	POSITION Z	PRESSURE P	VELOCITY W	FLUID TEMPERATURE T	WALL TEMPERATURE TWI
1	.000	1.000000	1.000000	1.000000	1.000000
2	.125	.999810	1.000000	1.000000	1.000000
3	.250	.999621	1.000001	1.000000	1.000000
4	.375	.999431	1.000001	1.000000	1.000000
5	.500	.999241	1.000001	1.000000	1.000000
6	.625	.999052	1.000001	1.000000	1.000000
7	.750	.998862	1.000001	1.000000	1.000000
8	.875	.998673	1.000002	1.000000	1.000000
9	1.000	.998483	1.000002	1.000000	1.000000

INLET PRESSURE P0 = 8640.000 LBF/SQ.FT
REF. VELOCITY W0 = .87128 FT/SEC
REF. TEMPERATURE T00 = 659.670 R

REYNOLDS NO = .30017+04
PRANDTL NO = 8.628066
DELTA = .001736
REL.PRESSURE IS .391534+04

INIT. NUSSELT NO. NU = .201856+02
WALL BIOT NO. BI = .485314-02

FIGURE 10(A) CONTINUED

SYSTEM PARAMETERS
****

TUBE LENGTH , XL = 12.000 FT
INTERNAL DIAMETER , DITB = .250 IN
WALL THICKNESS , STB = .100 IN
MATERIAL ALUMINUM
MASS (ALL TUBES) , MTB = 15.4480 LBM
NUMBER OF TUBES, NTBS = 10

FIN HEIGHT , HFN = 6.000 IN
THICKNESS AT ROOT , SROOT = .050 IN
THICKNESS AT TIP , STIP = .050 IN
MATERIAL ALUMINUM
MASS (ALL FINS) , MFN = 84.2960 LBM
NO. OF FIN SIDES RADIATING = 1

COOLANT FLUID IS SILICONE OIL
MASS (IN ALL TUBES) , MFL = 19.1289 LBM

PROTECTION LAYER THICKNESS, SMP = .011 IN
MASS, MMP = 2.038 LBM
MATERIAL IS BERYLLIUM

TOTAL MASS (EXCL. MANIFLD.) MTOT = 120.9104 LBM

TOTAL AREA (SINGLE NORMAL PROJECTION) ,
ATOT = 124,5000 SQ FT

FIGURE 10(A) CONTINUED

1131

ELAPSED TIME IS	.0000 HR ,	RELATIVE TIME IS	.0000	1 INTEGR. STEPS	
ALTITUDE IS	.00 FT ,	VELOCITY IS	.00 FT/SEC ,	ATM. TEMPERATURE IS	518.67 R

02

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .3289+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .0000 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = -.1924+05 BTU/HR
ENERGY STORAGE RATE, STORG = -.5213+05 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.8477	1.0000	1.0000	1.0000	1.0000	1.0000
.125	.8451	1.0000	1.0000	1.0000	1.0000	1.0000
.250	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
.375	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
.500	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
.625	.8430	1.0000	1.0000	1.0000	1.0000	1.0000
.750	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
.875	.8451	1.0000	1.0000	1.0000	1.0000	1.0000
1.000 (EXIT)	.8477	1.0000	1.0000	1.0000	1.0000	1.0000

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .276866+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .500488-01 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	1.0000	1.0000	.000000	.00000
.125	.99981	1.0000	1.0000	1.0000	1.0000	.000138	.02563
.250	.99962	1.0000	1.0000	1.0000	1.0000	.000242	.09431
.375	.99943	1.0000	1.0000	1.0000	1.0000	.000311	.19375
.500	.99924	1.0000	1.0000	1.0000	1.0000	.000380	.31625
.625	.99905	1.0000	1.0000	1.0000	1.0000	.000450	.46386
.750	.99886	1.0000	1.0000	1.0000	1.0000	.000484	.63147
.875	.99867	1.0000	1.0000	1.0000	1.0000	.000519	.80933
1.000 (EXIT)	.99848	1.0000	1.0000	1.0000	1.0000	.000553	1.00000

FIGURE 10(A) CONTINUED

ELAPSED TIME IS .0250 HR , RELATIVE TIME IS 6.5344 38 INTEGR. STEPS
ALTITUDE IS 56495.86 FT , VELOCITY IS 1449.87 FT/SEC , ATM. TEMPERATURE IS 389.97 R

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION

****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .2115+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .2443+04 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = -.1634+05 BTU/HR
ENERGY STORAGE RATE, STORG = -.3076+05 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	1.2195	1.0879	1.0879	1.0879	1.0879	1.0879
.125	.6981	.9517	.8626	.8047	.7764	.7689
.250	.3854	.9572	.8687	.8112	.7832	.7759
.375	.3856	.9550	.8680	.8110	.7832	.7758
.500	.3860	.9574	.8691	.8115	.7834	.7760
.625	.2817	.9560	.8704	.8141	.7866	.7793
.750	.3870	.9585	.8697	.8117	.7835	.7760
.875	.7019	.9489	.8620	.8044	.7762	.7687
1.000 (EXIT)	1.2263	1.0893	1.0893	1.0893	1.0893	1.0893

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER

****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .234041+05 BTU/HR
INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .428260+04 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURE TF	WALL TEMPERATURE TWI	PROTECT. LAYER TEMPERATURE TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	1.0879	1.0879	-186.124290	.00000
.125	.99981	.9956	.9867	.9517	.9517	74.285834	-.11604
.250	.99962	.9928	.9871	.9572	.9572	63.325497	.30202
.375	.99942	.9913	.9760	.9550	.9550	44.420708	.52840
.500	.99923	.9896	.9815	.9574	.9574	50.998492	.75807
.625	.99904	.9891	.9689	.9560	.9560	27.315979	.98675
.750	.99885	.9881	.9807	.9585	.9585	46.887507	1.14491
.875	.99866	.9868	.9641	.9489	.9489	32.308490	1.38225
1.000 (EXIT)	.99847	.9970	.9754	1.0893	1.0893	-241.334110	1.00000

FIGURE 10(A) CONTINUED

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ELAPSED TIME IS .0500 HR ,	RELATIVE TIME IS 13.0687	55 INTEGR. STEPS	
ALTITUDE IS 194986.66 FT ,	VELOCITY IS 6199.57 FT/SEC ,	ATM. TEMPERATURE IS 462.40 R	

2

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .2358+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .2680+03 BTU/HR ,
INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .2487+05 BTU/HR
ENERGY STORAGE RATE, STORG = .1333+05 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7697	.9783	.9783	.9783	.9783	.9783
.125	.6604	.9172	.9160	.9160	.9152	.9147
.250	.5928	.9214	.9231	.9249	.9252	.9250
.375	.5873	.9133	.9177	.9216	.9231	.9233
.500	.5825	.9130	.9182	.9223	.9238	.9240
.625	.5725	.9076	.9160	.9225	.9254	.9261
.750	.5751	.9070	.9147	.9204	.9227	.9231
.875	.5904	.8927	.9012	.9077	.9106	.9112
1.000 (EXIT)	.6184	.9315	.9315	.9315	.9315	.9315

FIGURE 10(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .159106+05 BTU/HR
INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .117761+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9783	.9783	42.947949	.00000
.125	.99981	.9927	.9814	.9172	.9172	126.966851	.14939
.250	.99961	.9874	.9750	.9214	.9214	106.037679	.33239
.375	.99942	.9827	.9603	.9133	.9133	92.991148	.47533
.500	.99923	.9784	.9561	.9130	.9130	85.266257	.61012
.625	.99904	.9748	.9429	.9076	.9076	69.837278	.72965
.750	.99885	.9714	.9416	.9070	.9070	68.399486	.83144
.875	.99866	.9677	.9290	.8927	.8927	71.936090	.93790
1.000 (EXIT)	.99847	.9672	.9252	.9315	.9315	-12.536525	1.00000

ELAPSED TIME IS .0750 HR , RELATIVE TIME IS 19.6031 80 INTEGR. STEPS
ALTITUDE IS 308492.96 FT , VELOCITY IS 11899.46 FT/SEC , ATM. TEMPERATURE IS 334.32 R

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .2231+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .2343+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .6611+04 BTU/HR
ENERGY STORAGE RATE, STORG = -.4995+04 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7313	.9671	.9671	.9671	.9671	.9671
.125	.6328	.9301	.9147	.9054	.9007	.8993
.250	.5703	.9322	.9199	.9128	.9093	.9084
.375	.5614	.9246	.9138	.9078	.9051	.9044
.500	.5533	.9224	.9127	.9075	.9051	.9046
.625	.5419	.9172	.9092	.9053	.9039	.9035
.750	.5395	.9146	.9068	.9030	.9015	.9012
.875	.5462	.9035	.8954	.8913	.8897	.8894
1.000 (EXIT)	.5620	.9121	.9121	.9121	.9121	.9121

FIGURE 10(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .172146+05 BTU/HR
INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .104721+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9671	.9671	67.116564	.00000
.125	.99981	.9939	.9852	.9301	.9301	112.356394	.15252
.250	.99961	.9892	.9780	.9322	.9322	93.483206	.31570
.375	.99942	.9850	.9670	.9246	.9246	86.350813	.44887
.500	.99923	.9811	.9610	.9224	.9224	78.735278	.57788
.625	.99904	.9778	.9515	.9172	.9172	69.991269	.69352
.750	.99885	.9746	.9473	.9146	.9146	66.729493	.79852
.875	.99866	.9712	.9386	.9035	.9035	71.472905	.90460
1.000 (EXIT)	.99847	.9690	.9329	.9121	.9121	42.267320	1.00000

ELAPSED TIME IS .1000 HR , RELATIVE TIME IS 26.1375 96 INTEGR. STEPS
ALTITUDE IS 330000.00 FT , VELOCITY IS 16499.06 FT/SEC , ATM. TEMPERATURE IS 376.50 R

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .2110+05 BTU/HR ,
CONU. FROM MANIFOLDS, CONDMF = .2680+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .8142+04 BTU/HR
ENERGY STORAGE RATE, STORG = -.1412+04 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7192	.9634	.9634	.9634	.9634	.9634
.125	.6096	.9257	.9074	.8948	.8876	.8852
.250	.5396	.9264	.9112	.9010	.8951	.8933
.375	.5289	.9186	.9048	.8955	.8902	.8885
.500	.5189	.9153	.9026	.8941	.8892	.8876
.625	.5029	.9096	.8984	.8910	.8867	.8854
.750	.5014	.9060	.8952	.8880	.8838	.8825
.875	.5144	.8959	.8848	.8772	.8728	.8714
1.000 (EXIT)	.542[illegible]	.9050	.9050	.9050	.9050	.9050

FIGURE 10(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .164041+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .112826+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9634	.9634	73.935921	.00000
.125	.99981	.9936	.9850	.9257	.9257	119.899873	.15022
.250	.99961	.9885	.9766	.9264	.9264	101.527077	.31116
.375	.99942	.9840	.9651	.9186	.9186	94.038617	.44474
.500	.99923	.9798	.9582	.9153	.9153	86.704713	.57414
.625	.99904	.9760	.9482	.9096	.9096	78.045426	.69177
.750	.99885	.9726	.9429	.9060	.9060	74.709270	.79958
.875	.99866	.9690	.9337	.8959	.8959	76.516509	.90673
1.000 (EXIT)	.99847	.9666	.9276	.9050	.9050	45.841238	1.00000

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ELAPSED TIME IS .1250 HR , RELATIVE TIME IS 32.6718 108 INTEGR. STEPS
ALTITUDE IS 313506.32 FT , VELOCITY IS 23548.28 FT/SEC , ATM. TEMPERATURE IS 341.94 R

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .2112+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .2058+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .2673+05 BTU/HR
ENERGY STORAGE RATE, STORG = .1783+05 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7023	.9583	.9583	.9583	.9583	.9583
.125	.6094	.9225	.9108	.9011	.8948	.8926
.250	.5488	.9222	.9136	.9061	.9013	.8995
.375	.5362	.9141	.9067	.9002	.8959	.8943
.500	.5244	.9098	.9036	.8979	.8940	.8926
.625	.5097	.9035	.8988	.8941	.8909	.8897
.750	.5033	.8991	.8949	.8905	.8874	.8862
.875	.5052	.8892	.8849	.8803	.8771	.8759
1.000 (EXIT)	.5154	.8951	.8951	.8951	.8951	.8951

FIGURE 10(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .156841+05 BTU/HR
INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .120026+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9583	.9583	83.797215	.00000
.125	.99981	.9934	.9847	.9225	.9225	124.993712	.14961
.250	.99961	.9880	.9755	.9222	.9222	107.109274	.30702
.375	.99942	.9832	.9637	.9141	.9141	99.836724	.43992
.500	.99923	.9787	.9559	.9098	.9098	92.636692	.56879
.625	.99904	.9747	.9455	.9035	.9035	84.442323	.68700
.750	.99885	.9709	.9393	.8991	.8991	80.657710	.79626
.875	.99866	.9670	.9298	.8892	.8892	81.486121	.90382
1.000 (EXIT)	.99847	.9642	.9229	.8951	.8951	55.786302	1.00000

ELAPSED TIME IS .1270 HR , RELATIVE TIME IS 33.1959 110 INTEGR. STEPS
ALTITUDE IS 310980.00 FT , VELOCITY IS 24234.00 FT/SEC , ATM. TEMPERATURE IS 337.93 R

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .2123+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .1911+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .3037+05 BTU/HR
ENERGY STORAGE RATE, STORG = .2135+05 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7001	.9576	.9576	.9576	.9576	.9576
.125	.6115	.9226	.9122	.9032	.8973	.8951
.250	.5534	.9222	.9149	.9081	.9036	.9019
.375	.5406	.9140	.9081	.9022	.8982	.8967
.500	.5286	.9097	.9049	.8998	.8962	.8949
.625	.5145	.9034	.9000	.8960	.8930	.8919
.750	.5072	.8989	.8961	.8923	.8895	.8884
.875	.5066	.8891	.8862	.8823	.8793	.8782
1.000 (EXIT)	.5127	.8941	.8941	.8941	.8941	.8941

FIGURE 10(A) CONCLUDED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .156649+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .120218+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9576	.9576	85.173653	.00000
.125	.99981	.9934	.9847	.9226	.9226	124.974236	.14983
.250	.99961	.9880	.9755	.9222	.9222	107.177940	.30672
.375	.99942	.9832	.9638	.9140	.9140	99.976870	.43945
.500	.99923	.9787	.9558	.9097	.9097	92.755548	.56813
.625	.99904	.9746	.9455	.9034	.9034	84.717443	.68622
.750	.99885	.9708	.9392	.8989	.8989	80.865383	.79553
.875	.99866	.9670	.9297	.8891	.8891	81.721740	.90304
1.000 (EXIT)	.99847	.9641	.9227	.8941	.8941	57.510110	1.00000

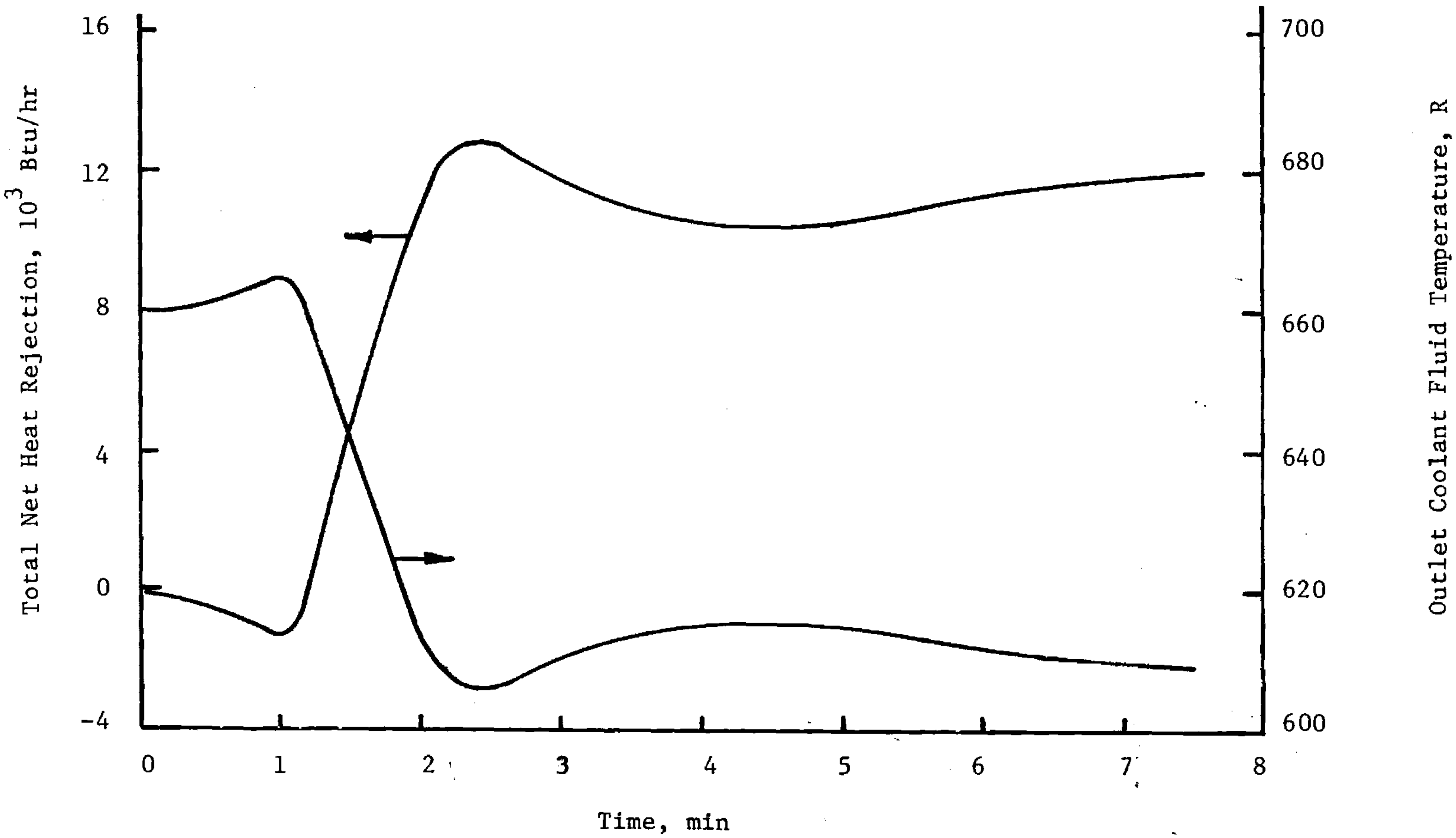

Fig. 10(b) System Response For Ascent-System Heat Rejection And Outlet Fluid Temperature

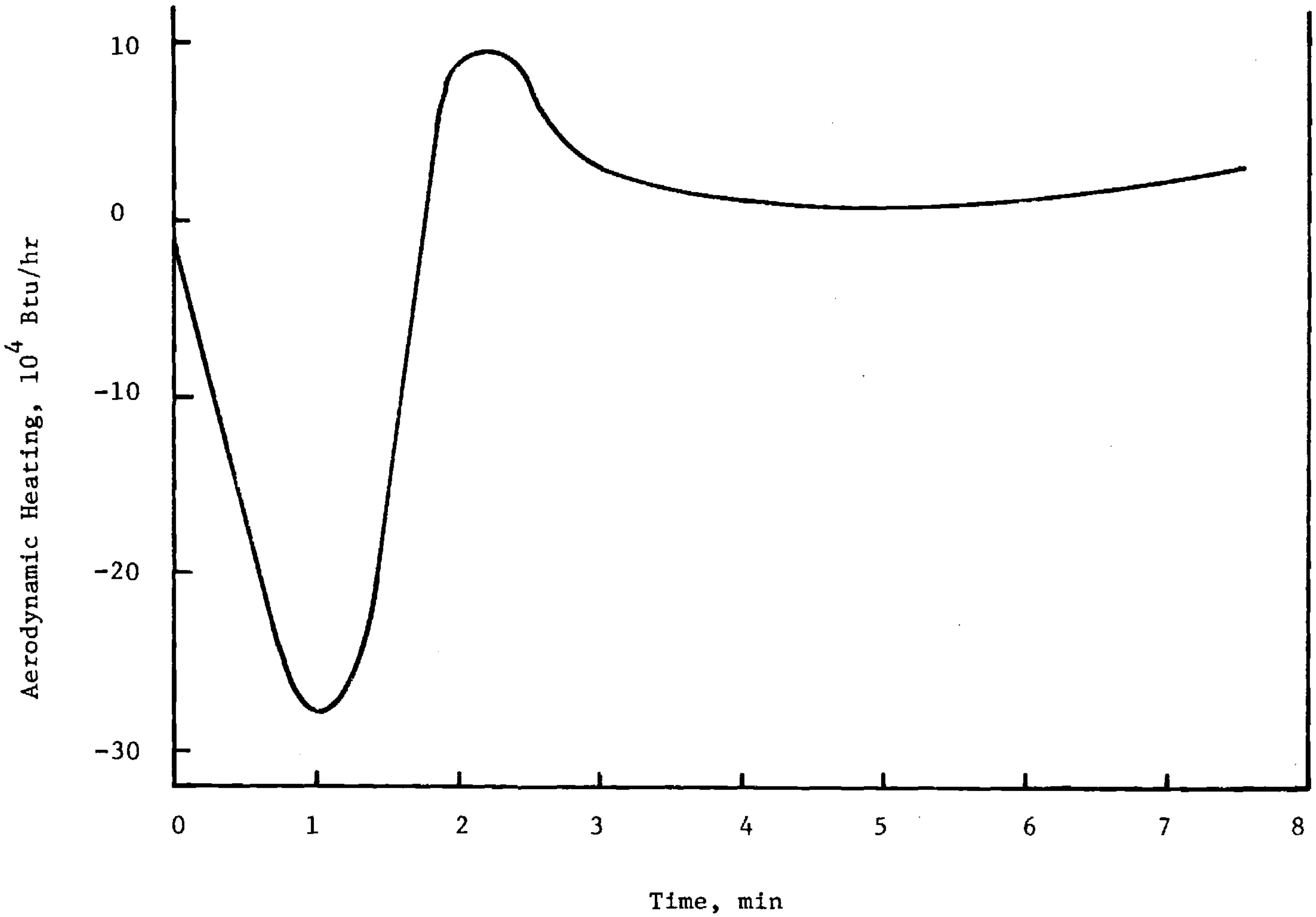

Fig. 11 Aerodynamic Heating For Ascent

b. Reentry

(i) Mission Description

The reentry altitude and velocity profiles used for the system output shown in Figures 13 and 14 are given in Figure 12. Input parameters for reentry are identical to those given in the mission description for ascent except for ICØNV which is set equal to 2 to designate reentry. The system parameters for reentry are printed prior to the current system output shown in Figure 13a.

(ii) System Response

The response of the radiator system during reentry is summarized in Figures 13 and 14. Figure 13 (a) provides selected program output showing current system conditions at various times during the reentry phase of the mission. Figure 13 (b) is a plot of the total heat rejection from the radiator system and the temperature of the coolant fluid at the exit plane of the flow channel. Figure 14 is a graph of the aerodynamic heating of the system as a function of time during the reentry phase of the mission.

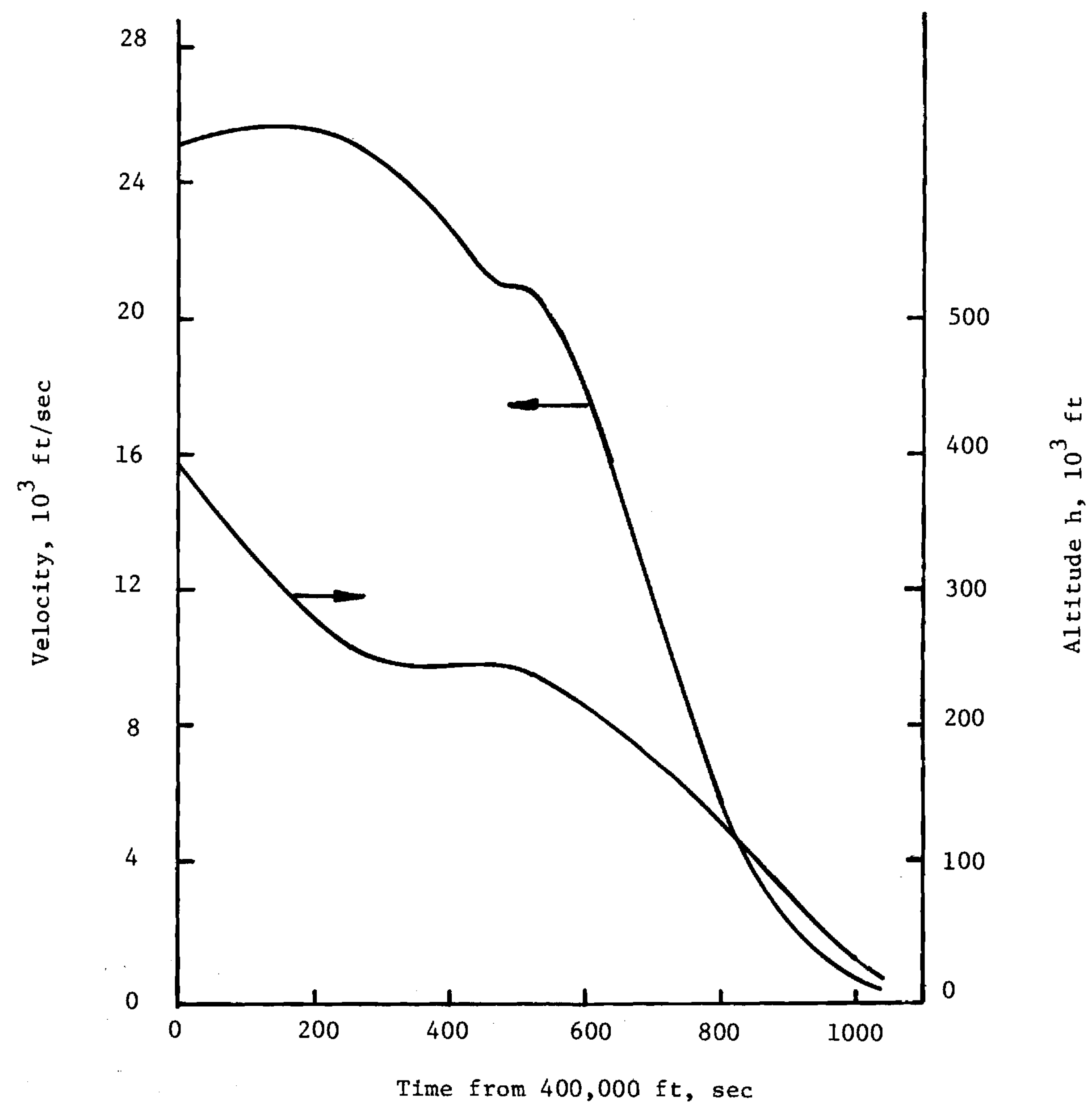

Fig. 12 Reentry Velocity and Altitude Profiles

```
$QNML
ITAPE   =              +0
ICASE   =              +0
NTM     =              +4
TO      =   .00000000E+00
PHN     =   .00000000E+00

$END
$TUBE
DITBI   =   .25000000E+00
STBI    =   .10000000E+00
XL      =   .12000000E+02
RHOTBI  =   .16859200E+03
MZ      =              +9
NRTBI   =              +3
NTBS    =             +10

$END
$FLOW
MDOTI   =   .50000000E+03
TO      =   .65967000E+03
PO      =   .86400000E+04

$END
$FIN
NX      =              +5
SROOTI  =   .50000000E-01
HFNI    =   .60000000E+01
STIPI   =   .50000000E-01
RHOFNI  =   .16859200E+03
STAGX   =   .20000000E+02
VERTX   =   .10000000E+02

$END
$PROILR
NRMP    =              +3
RHOMPI  =   .16859200E+03
RHOMCT  =   .50000000E+00
VELM    =   .65600000E+05
TAU     =   .36500000E+04
PROB    =   .99000000E+00
ALPHA   =   .18800000E-09
BTA     =   .12130000E+01
GAMMA   =   .15000000E+01
PHI     =   .50000000E+00
THETA   =   .66666700E+00
ATK     =   .17500000E+01
AN      =   .10000000E+01

$END
$MANIFD
AMAN    =   .43000000E+02

$END
$RUNOPT
MSTOTR  =              +2
```

FIGURE 13(A) SYSTEM RESPONSE FOR REENTRY
PROGRAM OUTPUT

```
DTWRTE  =     .16667000E-01
TEND    =     .29400000E+00
ALIMIT  =     .50000000E-04
RLIMIT  =     .10000000E-04
TI      =     .65967000E+03
LIMWRT  =               +25
NCONV   =                +2
LTT     =                +0
LFLD    =                +1
LTS     =                +0

$END
```

FIGURE 13(A) CONTINUED

INITIAL LINE CONDITIONS
******* **** **********
(ALL QUANTITIES ARE NORMALIZED)

PT.NO.	POSITION Z	PRESSURE P	VELOCITY W	FLUID TEMPERATURE T	WALL TEMPERATURE TWI
1	.000	1.000000	1.000000	1.000000	1.000000
2	.125	.999810	1.000000	1.000000	1.000000
3	.250	.999621	1.000001	1.000000	1.000000
4	.375	.999431	1.000001	1.000000	1.000000
5	.500	.999241	1.000001	1.000000	1.000000
6	.625	.999052	1.000001	1.000000	1.000000
7	.750	.998862	1.000001	1.000000	1.000000
8	.875	.998673	1.000002	1.000000	1.000000
9	1.000	.998483	1.000002	1.000000	1.000000

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INLET PRESSURE PO = 8640.000 LBF/SQ.FT
REF. VELOCITY WO = .87128 FT/SEC
REF. TEMPERATURE TOO = 659.670 R

REYNOLDS NO = .30017+04
PRANDTL NO = 8.628066
DELTA = .001736
REL.PRESSURE IS .391534+04

INIT. NUSSELT NO. NU = .201856+02
WALL BIOT NO. BI = .485314-02

FIGURE 13(A) CONTINUED

SYSTEM PARAMETERS
****

TUBE LENGTH , XL = 12.000 FT
INTERNAL DIAMETER , DITB = .250 IN
WALL THICKNESS , STB = .100 IN
MATERIAL ALUMINUM
MASS (ALL TUBES) , MTB = 15.4480 LBM
NUMBER OF TUBES, NTBS = 10

FIN HEIGHT , HFN = 6.000 IN
THICKNESS AT ROOT , SROOT = .050 IN
THICKNESS AT TIP , STIP = .050 IN
MATERIAL ALUMINUM
MASS (ALL FINS) , MFN = 84.2960 LBM
NO. OF FIN SIDES RADIATING = 1

COOLANT FLUID IS SILICONE OIL
MASS (IN ALL TUBES) , MFL = 19.1289 LBM

PROTECTION LAYER THICKNESS, SMP = .011 IN
MASS, MMP = 2.038 LBM
MATERIAL IS BERYLLIUM

TOTAL MASS (EXCL. MANIFLD.) MTOT = 120.9104 LBM

TOTAL AREA (SINGLE NORMAL PROJECTION) ,
ATOT = 124.5000 SQ FT

02

FIGURE 13(A) CONTINUED

ELAPSED TIME IS .0000 HR , RELATIVE TIME IS .0000 1 INTEGR. STEPS
ALTITUDE IS 394000.00 FT , VELOCITY IS 25400.00 FT/SEC , ATM. TEMPERATURE IS 661.41 R

02

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .3289+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .0000 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .6237+04 BTU/HR
ENERGY STORAGE RATE, STORG = -.2665+05 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.8477	1.0000	1.0000	1.0000	1.0000	1.0000
.125	.8451	1.0000	1.0000	1.0000	1.0000	1.0000
.250	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
.375	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
.500	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
.625	.8430	1.0000	1.0000	1.0000	1.0000	1.0000
.750	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
.875	.8451	1.0000	1.0000	1.0000	1.0000	1.0000
1.000 (EXIT)	.8477	1.0000	1.0000	1.0000	1.0000	1.0000

FIGURE 13(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .276866+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .500488-01 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	1.0000	1.0000	.000000	.00000
.125	.99981	1.0000	1.0000	1.0000	1.0000	.000138	.02563
.250	.99962	1.0000	1.0000	1.0000	1.0000	.000242	.09431
.375	.99943	1.0000	1.0000	1.0000	1.0000	.000311	.19375
.500	.99924	1.0000	1.0000	1.0000	1.0000	.000380	.31625
.625	.99905	1.0000	1.0000	1.0000	1.0000	.000450	.46386
.750	.99886	1.0000	1.0000	1.0000	1.0000	.000484	.63147
.875	.99867	1.0000	1.0000	1.0000	1.0000	.000519	.80933
1.000 (EXIT)	.99848	1.0000	1.0000	1.0000	1.0000	.000553	1.00000

```
DTWRTE  =    .16667000E-01
TEND    =    .29400000E+00
ALIMIT  =    .50000000E-04
RLIMIT  =    .10000000E-04
TI      =    .65967000E+03
LIMWRT  =              +25
NCONV   =               +2
LTT     =               +0
LFLD    =               +1
LTS     =               +0

$END
```

FIGURE 13(A) CONTINUED

INITIAL LINE CONDITIONS
******* **** **********
(ALL QUANTITIES ARE NORMALIZED)

PT.NO.	POSITION Z	PRESSURE P	VELOCITY W	FLUID TEMPERATURE T	WALL TEMPERATURE TWI
1	.000	1.000000	1.000000	1.000000	1.000000
2	.125	.999810	1.000000	1.000000	1.000000
3	.250	.999621	1.000001	1.000000	1.000000
4	.375	.999431	1.000001	1.000000	1.000000
5	.500	.999241	1.000001	1.000000	1.000000
6	.625	.999052	1.000001	1.000000	1.000000
7	.750	.998862	1.000001	1.000000	1.000000
8	.875	.998673	1.000002	1.000000	1.000000
9	1.000	.998483	1.000002	1.000000	1.000000

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INLET PRESSURE PO = 8640.000 LBF/SQ.FT
REF. VELOCITY WO = .87128 FT/SEC
REF. TEMPERATURE TOO = 659.670 R

REYNOLDS NO = .30017+04
PRANDTL NO = 8.628066
DELTA = .001736
REL.PRESSURE IS .391534+04

INIT. NUSSELT NO. NU = .201856+02
WALL BIOT NO. BI = .485314-02

FIGURE 13(A) CONTINUED

SYSTEM PARAMETERS
****

TUBE LENGTH , XL = 12.000 FT
INTERNAL DIAMETER , DITB = .250 IN
WALL THICKNESS , STB = .100 IN
MATERIAL ALUMINUM
MASS (ALL TUBES) , MTB = 15.4480 LBM
NUMBER OF TUBES, NTBS = 10

FIN HEIGHT , HFN = 6.000 IN
THICKNESS AT ROOT , SROOT = .050 IN
THICKNESS AT TIP , STIP = .050 IN
MATERIAL ALUMINUM
MASS (ALL FINS) , MFN = 84.2960 LBM
NO. OF FIN SIDES RADIATING = 1

COOLANT FLUID IS SILICONE OIL
MASS (IN ALL TUBES) , MFL = 19.1289 LBM

PROTECTION LAYER THICKNESS, SMP = .011 IN
MASS, MMP = 2.038 LBM
MATERIAL IS BERYLLIUM

TOTAL MASS (EXCL. MANIFLD.) MTOT = 120.9104 LBM

TOTAL AREA (SINGLE NORMAL PROJECTION) ,
ATOT = 124.5000 SQ FT

FIGURE 13(A) CONTINUED

ELAPSED TIME IS .0000 HR , RELATIVE TIME IS .0000 1 INTEGR. STEPS
ALTITUDE IS 394000.00 FT , VELOCITY IS 25400.00 FT/SEC , ATM. TEMPERATURE IS 661.41 R

02

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .3289+05 BTU/HR ,
CONU. FROM MANIFOLDS, CONDMF = .0000 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .6237+04 BTU/HR
ENERGY STORAGE RATE, STORG = -.2665+05 BTU/HR

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AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.8477	1.0000	1.0000	1.0000	1.0000	1.0000
.125	.8451	1.0000	1.0000	1.0000	1.0000	1.0000
.250	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
.375	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
.500	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
.625	.8430	1.0000	1.0000	1.0000	1.0000	1.0000
.750	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
.875	.8451	1.0000	1.0000	1.0000	1.0000	1.0000
1.000 (EXIT)	.8477	1.0000	1.0000	1.0000	1.0000	1.0000

FIGURE 13(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .276866+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .500488-01 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	1.0000	1.0000	.000000	.00000
.125	.99981	1.0000	1.0000	1.0000	1.0000	.000138	.02563
.250	.99962	1.0000	1.0000	1.0000	1.0000	.000242	.09431
.375	.99943	1.0000	1.0000	1.0000	1.0000	.000311	.19375
.500	.99924	1.0000	1.0000	1.0000	1.0000	.000380	.31625
.625	.99905	1.0000	1.0000	1.0000	1.0000	.000450	.46386
.750	.99886	1.0000	1.0000	1.0000	1.0000	.000484	.63147
.875	.99867	1.0000	1.0000	1.0000	1.0000	.000519	.80933
1.000 (EXIT)	.99848	1.0000	1.0000	1.0000	1.0000	.000553	1.00000

ELAPSED TIME IS .0500 HR , RELATIVE TIME IS 13.0695 36 INTEGR. STEPS
ALTITUDE IS 292998.55 FT , VELOCITY IS 25799.98 FT/SEC , ATM. TEMPERATURE IS 325.17 R

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .2773+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = -.9819+02 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .5638+05 BTU/HR
ENERGY STORAGE RATE, STORG = .3510+05 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7159	.9625	.9625	.9625	.9625	.9625
.125	.7255	.9584	.9678	.9711	.9720	.9719
.250	.7293	.9556	.9662	.9703	.9716	.9717
.375	.7242	.9527	.9643	.9690	.9707	.9709
.500	.7198	.9500	.9626	.9679	.9699	.9702
.625	.7259	.9478	.9610	.9668	.9691	.9694
.750	.7126	.9458	.9598	.9662	.9687	.9691
.875	.6797	.9441	.9589	.9657	.9684	.9690
1.000 (EXIT)	.6273	.9345	.9345	.9345	.9345	.9345

FIGURE 13(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .211383+05 BTU/HR
INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .654839+04 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9625	.9625	80.776558	.00000
.125	.99981	.9963	.9925	.9584	.9584	73.419073	.17633
.250	.99962	.9931	.9856	.9556	.9556	64.706697	.33361
.375	.99943	.9902	.9799	.9527	.9527	58.594118	.47323
.500	.99924	.9877	.9742	.9500	.9500	51.918591	.59957
.625	.99905	.9854	.9698	.9478	.9478	47.317073	.71200
.750	.99886	.9834	.9649	.9458	.9458	41.271317	.81355
.875	.99867	.9816	.9619	.9441	.9441	38.321868	.90322
1.000 (EXIT)	.99848	.9794	.9578	.9345	.9345	50.009891	1.00000

ELAPSED TIME IS .1000 HR , RELATIVE TIME IS 26.1390 60 INTEGR. STEPS
ALTITUDE IS 245000.71 FT , VELOCITY IS 23799.82 FT/SEC , ATM. TEMPERATURE IS 362.54 R

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION

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REFERENCE TEMPERATURE, TOO = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .5506+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = -.1573+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .1775+06 BTU/HR
ENERGY STORAGE RATE, STORG = .1193+06 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.6299	.9354	.9354	.9354	.9354	.9354
.125	1.2481	1.0371	1.1389	1.2022	1.2359	1.2459
.250	1.6155	1.0278	1.1252	1.1849	1.2163	1.2254
.375	1.6061	1.0297	1.1254	1.1843	1.2153	1.2243
.500	1.5974	1.0254	1.1221	1.1816	1.2130	1.2222
.625	1.7098	1.0252	1.1178	1.1745	1.2043	1.2130
.750	1.5816	1.0219	1.1189	1.1789	1.2106	1.2200
.875	1.2127	1.0341	1.1332	1.1958	1.2296	1.2398
1.000 (EXIT)	.6032	.9265	.9265	.9265	.9265	.9265

FIGURE 13(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER

REFERENCE TEMPERATURE, TOO = 659.670 R
REFERENCE PRESSURE, POO = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, WOO = .871 FT/SEC
COOLANT POWER, INLET AT T=TO HO = .276867+05 BTU/HR
EXIT CURRENTLY EI = .307355+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = -.304877+04 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TWI	PROTECT. LAYER TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9354	.9354	160.289324	.00000
.125	.99981	1.0040	1.0125	1.0371	1.0371	-61.108924	-.30040
.250	.99962	1.0060	1.0110	1.0278	1.0278	-41.625156	.64967
.375	.99944	1.0070	1.0198	1.0297	1.0297	-24.422209	1.00147
.500	.99925	1.0081	1.0143	1.0254	1.0254	-27.635271	1.36675
.625	.99906	1.0079	1.0242	1.0252	1.0252	-2.552186	1.66864
.750	.99887	1.0084	1.0127	1.0219	1.0219	-23.023775	1.76029
.875	.99868	1.0095	1.0268	1.0341	1.0341	-18.077758	2.15741
1.000 (EXIT)	.99850	1.0004	1.0171	.9265	.9265	224.826389	1.00000

ELAPSED TIME IS .1500 HR , RELATIVE TIME IS 39.2085 86 INTEGR. STEPS
ALTITUDE IS 234996.24 FT , VELOCITY IS 20199.73 FT/SEC , ATM. TEMPERATURE IS 384.00 R

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .6486+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .4866+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .1582+06 BTU/HR
ENERGY STORAGE RATE, STORG = .8051+05 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION θ	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7198	.9636	.9636	.9636	.9636	.9636
.125	1.4150	1.0926	1.1935	1.2578	1.2935	1.3045
.250	1.8367	1.0752	1.1646	1.2196	1.2491	1.2579
.375	1.8485	1.0866	1.1724	1.2249	1.2530	1.2614
.500	1.8592	1.0847	1.1701	1.2224	1.2504	1.2587
.625	1.9854	1.0895	1.1675	1.2141	1.2385	1.2456
.750	1.8776	1.0901	1.1738	1.2249	1.2523	1.2605
.875	1.5358	1.1232	1.2130	1.2699	1.3012	1.3108
1.000 (EXIT)	.9599	1.0290	1.0290	1.0290	1.0290	1.0290

FIGURE 13(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .410317+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = -.133450+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TWI	PROTECT. LAYER TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9636	.9636	99.048074	.00000
.125	.99982	1.0106	1.0293	1.0926	1.0926	-172.390614	.11927
.250	.99963	1.0168	1.0327	1.0752	1.0752	-115.685914	.35437
.375	.99944	1.0217	1.0514	1.0866	1.0866	-95.888686	.48609
.500	.99926	1.0265	1.0507	1.0847	1.0847	-92.660016	.62721
.625	.99907	1.0295	1.0694	1.0895	1.0895	-54.798841	.74575
.750	.99888	1.0332	1.0604	1.0901	1.0901	-80.840606	.83365
.875	.99869	1.0390	1.0841	1.1232	1.1232	-106.374774	.97867
1.000 (EXIT)	.99850	1.0341	1.0833	1.0290	1.0290	147.963610	1.00000

ELAPSED TIME IS .2000 HR , RELATIVE TIME IS 52.2780 112 INTEGR. STEPS
ALTITUDE IS 171993.57 FT , VELOCITY IS 10399.29 FT/SEC , ATM. TEMPERATURE IS 487.17 R

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FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .7602+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .6873+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .1290+06 BTU/HR
ENERGY STORAGE RATE, STORG = .3334+05 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7486	.9722	.9722	.9722	.9722	.9722
.125	1.6110	1.1342	1.2450	1.3218	1.3667	1.3813
.250	2.1382	1.1092	1.2023	1.2645	1.2997	1.3108
.375	2.1632	1.1263	1.2145	1.2735	1.3069	1.3174
.500	2.1871	1.1246	1.2119	1.2703	1.3035	1.3139
.625	2.3489	1.1324	1.2094	1.2598	1.2879	1.2966
.750	2.2311	1.1341	1.2190	1.2759	1.3083	1.3186
.875	1.8337	1.1830	1.2782	1.3448	1.3840	1.3968
1.000 (EXIT)	1.1567	1.0745	1.0745	1.0745	1.0745	1.0745

FIGURE 13(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .479690+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = -.202823+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9722	.9722	81.004254	.00000
.125	.99982	1.0161	1.0436	1.1342	1.1342	-263.760815	.13900
.250	.99963	1.0255	1.0499	1.1092	1.1092	-172.715717	.35778
.375	.99945	1.0330	1.0764	1.1263	1.1263	-145.424294	.48221
.500	.99926	1.0403	1.0770	1.1246	1.1246	-138.439034	.61517
.625	.99907	1.0450	1.1030	1.1324	1.1324	-85.539244	.72615
.750	.99889	1.0508	1.0923	1.1341	1.1341	-121.559476	.81088
.875	.99870	1.0600	1.1250	1.1830	1.1830	-168.841410	.94894
1.000 (EXIT)	.99851	1.0553	1.1270	1.0745	1.0745	152.930897	1.00000

ELAPSED TIME IS .2500 HR , RELATIVE TIME IS 65.3475 138 INTEGR. STEPS
ALTITUDE IS 74990.18 FT , VELOCITY IS 2199.64 FT/SEC , ATM. TEMPERATURE IS 394.97 R

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .6239+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .1221+04 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = -.2252+05 BTU/HR
ENERGY STORAGE RATE, STORG = -.1037+06 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X				
		.00000	.25000	.50000	.75000	1.00000
.000	.7413	.9700	.9700	.9700	.9700	.9700
.125	1.3374	1.1293	1.1889	1.2386	1.2700	1.2810
.250	1.7043	1.1026	1.1505	1.1899	1.2143	1.2227
.375	1.7279	1.1216	1.1633	1.1992	1.2217	1.2295
.500	1.7503	1.1191	1.1605	1.1961	1.2186	1.2263
.625	1.8472	1.1295	1.1613	1.1902	1.2035	1.2149
.750	1.7916	1.1300	1.1681	1.2021	1.2237	1.2313
.875	1.5837	1.1812	1.2224	1.2614	1.2871	1.2965
1.000 (EXIT)	1.2233	1.0887	1.0887	1.0887	1.0887	1.0887

FIGURE 13(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .476853+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = -.199986+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TF	WALL TWI	PROTECT. LAYER TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	FRACTION OF TOTAL
			T E M P E R A T U R E S				
.000	1.00000	1.0000	1.0000	.9700	.9700	86.688877	.00000
.125	.99982	1.0156	1.0433	1.1293	1.1293	-248.916988	.13119
.250	.99963	1.0244	1.0473	1.1026	1.1026	-160.148674	.34140
.375	.99945	1.0316	1.0739	1.1216	1.1216	-138.130276	.45934
.500	.99926	1.0386	1.0735	1.1191	1.1191	-132.202616	.58956
.625	.99907	1.0434	1.0996	1.1295	1.1295	-86.335973	.69966
.750	.99889	1.0491	1.0895	1.1300	1.1300	-117.345061	.78642
.875	.99870	1.0585	1.1210	1.1812	1.1812	-174.303867	.92608
1.000 (EXIT)	.99851	1.0560	1.1255	1.0887	1.0887	106.599895	1.00000

ELAPSED TIME IS .2667 HR , RELATIVE TIME IS 69.7040 148 INTEGR. STEPS
ALTITUDE IS 48989.54 FT , VELOCITY IS 1199.81 FT/SEC , ATM. TEMPERATURE IS 389.97 R

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .3745+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .1843+04 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = -.1705+06 BTU/HR
ENERGY STORAGE RATE, STORG = -.2212+06 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.8631	1.0041	1.0041	1.0041	1.0041	1.0041
.125	.8816	1.0874	1.0392	1.0268	1.0269	1.0292
.250	.8987	1.0677	1.0163	1.0006	.9982	.9996
.375	.9144	1.0850	1.0277	1.0084	1.0042	1.0050
.500	.9291	1.0834	1.0259	1.0064	1.0022	1.0031
.625	.8896	1.0947	1.0311	1.0076	1.0010	1.0010
.750	.9553	1.0951	1.0334	1.0117	1.0065	1.0070
.875	1.1262	1.1330	1.0672	1.0442	1.0388	1.0396
1.000 (EXIT)	1.4023	1.1242	1.1242	1.1242	1.1242	1.1242

FIGURE 13(A) CONCLUDED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .427089+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = -.150223+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	1.0041	1.0041	-11.239679	.00000
.125	.99982	1.0103	1.0296	1.0874	1.0874	-156.783590	.13991
.250	.99963	1.0160	1.0308	1.0677	1.0677	-99.922624	.30879
.375	.99944	1.0212	1.0497	1.0850	1.0850	-95.677561	.41267
.500	.99926	1.0262	1.0508	1.0834	1.0834	-88.377534	.53137
.625	.99907	1.0306	1.0683	1.0947	1.0947	-71.594559	.63305
.750	.99888	1.0348	1.0667	1.0951	1.0951	-77.058642	.72233
.875	.99869	1.0421	1.0839	1.1330	1.1330	-133.142769	.84743
1.000 (EXIT)	.99850	1.0474	1.0955	1.1242	1.1242	-78.039950	1.00000

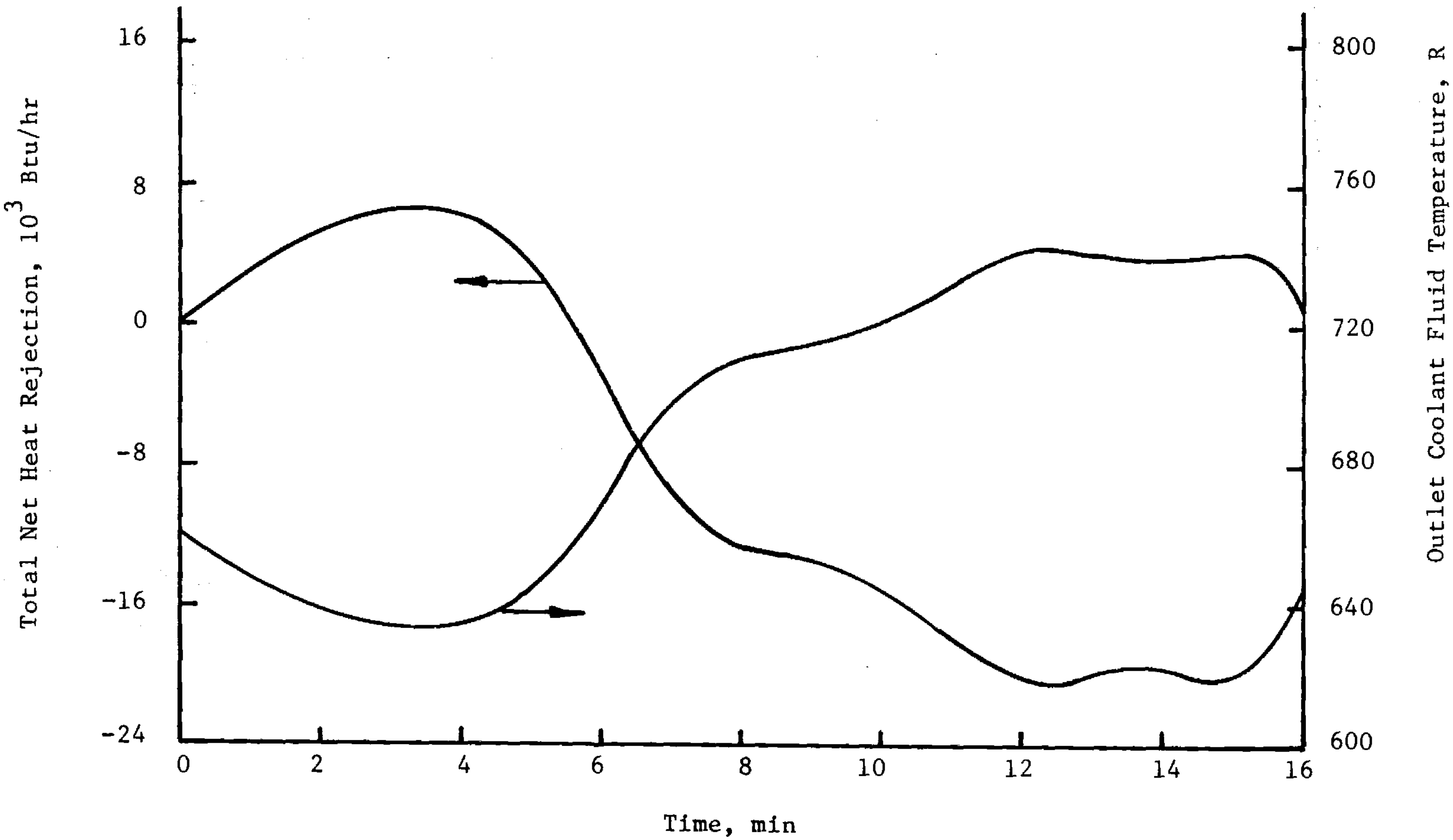

Fig. 13(b) System Response For Reentry-Heat Rejection And Outlet Fluid Temperature

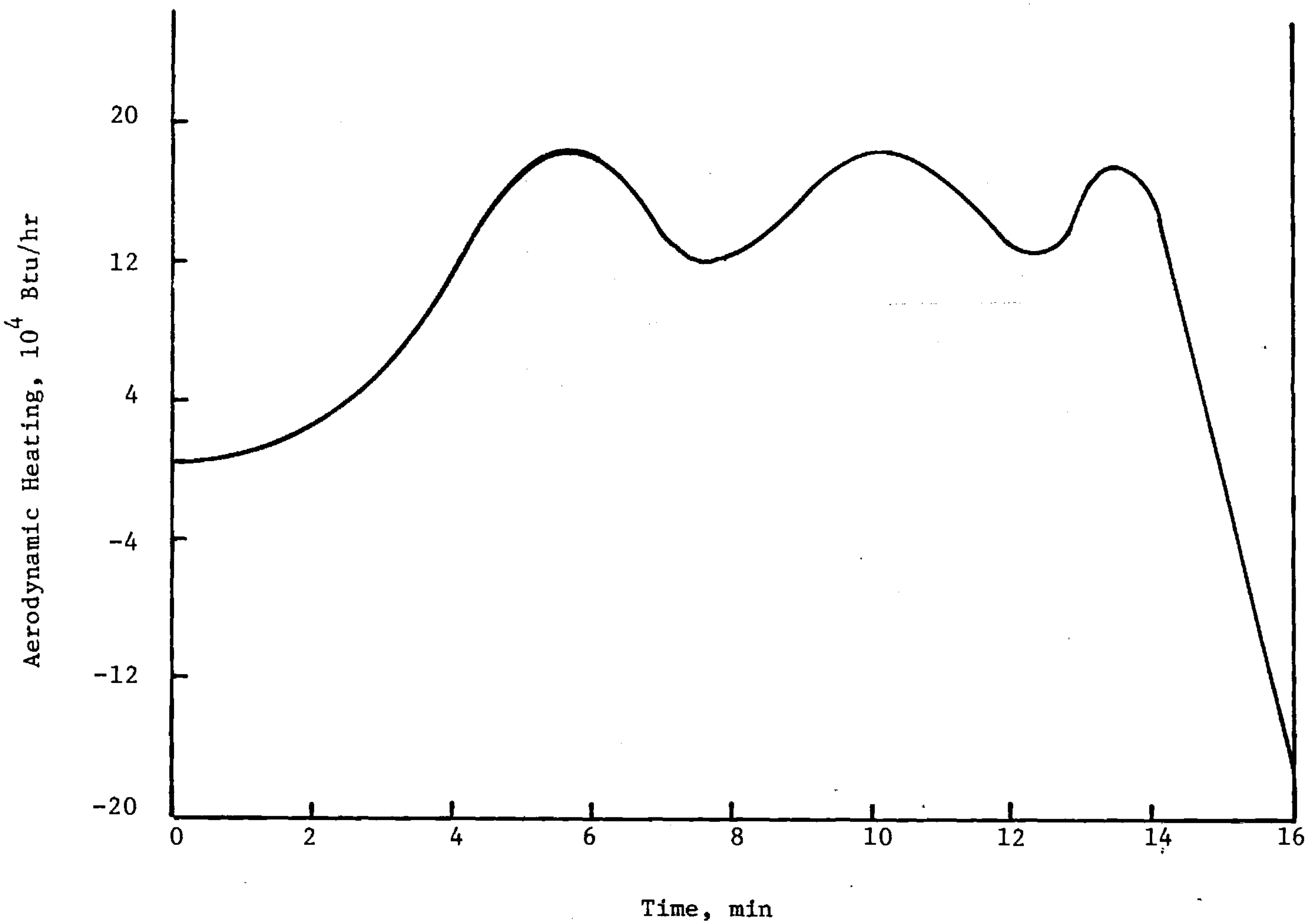

Fig.14 Aerodynamic Heating For Reentry

c. Orbital Mission

(i) Mission Description

Transient system performance is predicted in Figure 16 for a typical space base orbital mission. The mission is described by a 270 nautical mile circular orbit inclined at 55°. Incident flux values for solar irradiation, earth albedo and earth irradiation were supplied by a previously executed MRI program with the flux data being transfered from magnetic tape.

Incident radiant flux values for a typical fin element are plotted as a function of time into orbit in Figure 15. Other input parameters which specify system geometry, material properties and fluid flow conditions are identical to those used for the ascent and reentry phases that were previously reported in sections 5a and 5b.

(ii) System Response

The response of the radiator system during the first twenty minutes of the orbit is summarized in Figures 16(a) and 16(b). Input parameters and a selected number of output listings of current radiator conditions are shown in Figure 16(a). Figure 16(b) graphically summarizes the outlet coolant fluid temperature and the total net heat rejection from the radiator for the same period during orbit.

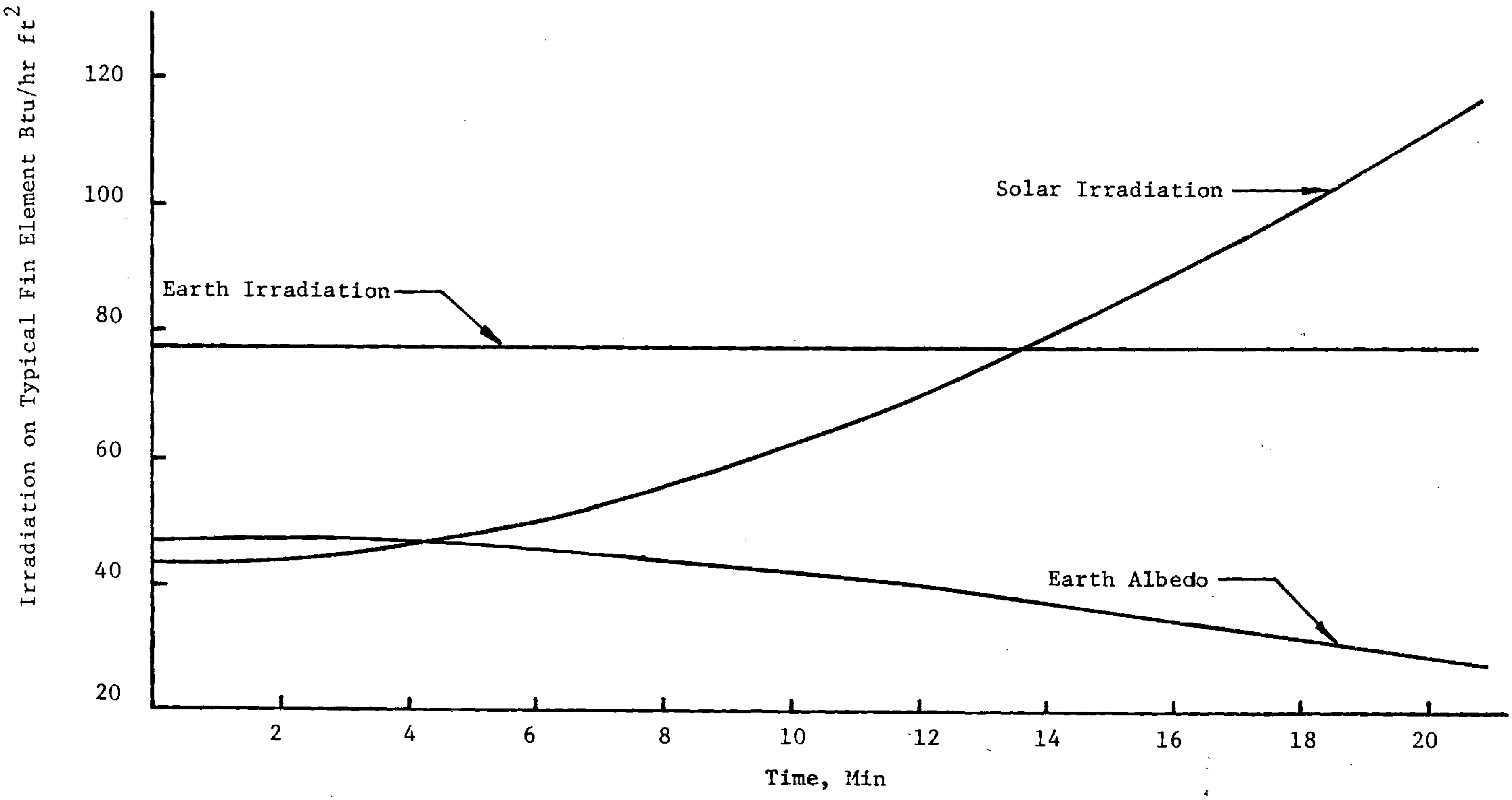

Fig. 15 Orbital Incident Fluxes

```
$GNML
ITAPE    =              +3
ICASE    =              +1
NTM      =             +73
TO       =   .00000000E+00
PHN      =   .00000000E+00

$END
$TUBE
DITBI    =   .25000000E+00
STBI     =   .10000000E+00
XL       =   .12000000E+02
RHOTBI   =   .16859200E+03
MZ       =              +9
NRTBI    =              +3
NTBS     =             +10

$END
$FLOW
MDOTI    =   .50000000E+03
TO       =   .65967000E+03
PO       =   .86400000E+04

$END
$FIN
NX       =              +5
SROOTI   =   .50000000E-01
HFNI     =   .60000000E+01
STIPI    =   .50000000E-01
RHOFNI   =   .16859200E+03
STAGX    =   .20000000E+02
VERTX    =   .10000000E+02

$END
$PROTLR
NRMP     =              +3
RHOMPI   =   .16859200E+03
RHOMET   =   .50000000E+00
VELM     =   .65600000E+05
TAU      =   .36500000E+04
PROB     =   .99000000E+00
ALPHA    =   .18800000E-09
BTA      =   .12130000E+01
GAMMA    =   .15000000E+01
PHI      =   .50000000E+00
THETA    =   .66666700E+00
ATK      =   .17500000E+01
AN       =   .10000000E+01

$END
$MANIFD
AMAN     =   .43000000E+02

$END
$RUNOPT
MSTOTR   =              +2
```

FIGURE 16(A) SYSTEM RESPONSE FOR ORBITAL MISSION
PROGRAM OUTPUT

```
DTWRITE  =     .35000000E-01
TEND     =     .70000000E+00
ALIMIT   =     .50000000E-04
RLIMIT   =     .10000000E-04
T1       =     .65967000E+03
LIMWRT   =               +25
NCONV    =                +0
LTT      =                +0
LFLD     =                +1
LTS      =                +0

$END
```

FIGURE 16(A) CONTINUED

INITIAL LINE CONDITIONS
******* **** **********
(ALL QUANTITIES ARE NORMALIZED)

PT.NO.	POSITION Z	PRESSURE P	VELOCITY W	FLUID TEMPERATURE T	WALL TEMPERATURE TWI
1	.000	1.000000	1.000000	1.000000	1.000000
2	.125	.999810	1.000000	1.000000	1.000000
3	.250	.999621	1.000001	1.000000	1.000000
4	.375	.999431	1.000001	1.000000	1.000000
5	.500	.999241	1.000001	1.000000	1.000000
6	.625	.999052	1.000001	1.000000	1.000000
7	.750	.998862	1.000001	1.000000	1.000000
8	.875	.998673	1.000002	1.000000	1.000000
9	1.000	.998483	1.000002	1.000000	1.000000

INLET PRESSURE PO = 8640.000 LBF/SQ.FT
REF. VELOCITY WO = .87128 FT/SEC
REF. TEMPERATURE TOO = 659.670 R

REYNOLDS NO = .30017+04
PRANDTL NO = 8.628066
DELTA = .001736
REL.PRESSURE IS .391534+04

FIGURE 16(A) CONTINUED

INIT. NUSSELT NO. NU = .201856+02
WALL BIOT NO. BI = .485314-02

SYSTEM PARAMETERS
****

TUBE LENGTH , XL = 12.000 FT
INTERNAL DIAMETER , DITB = .250 IN
WALL THICKNESS , STB = .100 IN
MATERIAL ALUMINUM
MASS (ALL TUBES) , MTB = 15.4480 LBM
NUMBER OF TUBES, NTBS = 10

FIN HEIGHT , HFN = 6.000 IN
THICKNESS AT ROOT , SROOT = .050 IN
THICKNESS AT TIP , STIP = .050 IN
MATERIAL ALUMINUM
MASS (ALL FINS) , MFN = 84.2960 LBM
NO. OF FIN SIDES RADIATING = 1

COOLANT FLUID IS SILICONE OIL
MASS (IN ALL TUBES) , MFL = 19.1289 LBM

PROTECTION LAYER THICKNESS, SMP = .011 IN
MASS, MMP = 2.038 LBM
MATERIAL IS BERYLLIUM

TOTAL MASS (EXCL. MANIFLD.) MTOT = 120.9104 LBM

TOTAL AREA (SINGLE NORMAL PROJECTION) ,
ATOT = 124.5000 SQ FT

FIGURE 16(A) CONTINUED

ELAPSED TIME IS .0000 HR
RELATIVE TIME IS .0000 **IN ORBIT** 1 INTEGR. STEPS

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .2114+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .0000 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .4326+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .1380+02 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.2114+05 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.5473	1.0000	1.0000	1.0000	1.0000	1.0000
.125	.5439	1.0000	1.0000	1.0000	1.0000	1.0000
.250	.5418	1.0000	1.0000	1.0000	1.0000	1.0000
.375	.5418	1.0000	1.0000	1.0000	1.0000	1.0000
.500	.5418	1.0000	1.0000	1.0000	1.0000	1.0000
.625	.5412	1.0000	1.0000	1.0000	1.0000	1.0000
.750	.5418	1.0000	1.0000	1.0000	1.0000	1.0000
.875	.5439	1.0000	1.0000	1.0000	1.0000	1.0000
1.000 (EXIT)	.5473	1.0000	1.0000	1.0000	1.0000	1.0000

FIGURE 16(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .276866+05 BTU/HR
INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .500488-01 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TF (TEMPERATURES)	WALL TWI (TEMPERATURES)	PROTECT. LAYER TMP (TEMPERATURES)	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	1.0000	1.0000	.000000	.00000
.125	.99981	1.0000	1.0000	1.0000	1.0000	.000138	.02563
.250	.99962	1.0000	1.0000	1.0000	1.0000	.000242	.09431
.375	.99943	1.0000	1.0000	1.0000	1.0000	.000311	.19375
.500	.99924	1.0000	1.0000	1.0000	1.0000	.000380	.31625
.625	.99905	1.0000	1.0000	1.0000	1.0000	.000450	.46386
.750	.99886	1.0000	1.0000	1.0000	1.0000	.000484	.63147
.875	.99867	1.0000	1.0000	1.0000	1.0000	.000519	.80933
1.000 (EXIT)	.99848	1.0000	1.0000	1.0000	1.0000	.000553	1.00000

ELAPSED TIME IS .0700 HR
RELATIVE TIME IS 18.2969 **IN ORBIT** 44 INTEGR. STEPS

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION

REFERENCE TEMPERATURE, T00 = 659.670 R
REF. RADIANT HEAT FLUX PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1368+05 BTU/HR
COND. FROM MANIFOLDS, CONDMF = .1925+03 BTU/HR

INCIDENT SOLAR FLUX, QSOLR = .4326+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .1313+02 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.7238+04 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.4812	.9816	.9816	.9816	.9816	.9816
.125	.3944	.9592	.9448	.9351	.9296	.9278
.250	.3403	.9581	.9453	.9368	.9320	.9305
.375	.3352	.9549	.9431	.9352	.9308	.9294
.500	.3306	.9527	.9415	.9341	.9299	.9286
.625	.3178	.9504	.9403	.9337	.9299	.9287
.750	.3230	.9485	.9386	.9320	.9283	.9271
.875	.3463	.9447	.9351	.9287	.9250	.9238
1.000 (EXIT)	.3877	.9538	.9538	.9538	.9538	.9538

FIGURE 16(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .214331+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .625357+04 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TWI	PROTECT. LAYER TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9816	.9816	39.721291	.00000
.125	.99981	.9963	.9919	.9592	.9592	70.315785	.15362
.250	.99962	.9933	.9863	.9581	.9581	60.747243	.32489
.375	.99943	.9907	.9801	.9549	.9549	54.229073	.46643
.500	.99924	.9883	.9758	.9527	.9527	49.817427	.59891
.625	.99905	.9862	.9704	.9504	.9504	43.049000	.71844
.750	.99886	.9842	.9676	.9485	.9485	41.208278	.82419
.875	.99867	.9824	.9626	.9447	.9447	38.468452	.92672
1.000 (EXIT)	.99848	.9816	.9600	.9538	.9538	13.438381	1.00000

143513

ELAPSED TIME IS .1400 HR
RELATIVE TIME IS 36.5939 **IN ORBIT** 74 INTEGR. STEPS

2

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

15

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1151+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .2601+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .4326+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .1164+02 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.2599+04 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.4690	.9777	.9777	.9777	.9777	.9777
.125	.3587	.9453	.9273	.9150	.9078	.9054
.250	.2888	.9446	.9290	.9184	.9122	.9102
.375	.2791	.9392	.9247	.9148	.9091	.9072
.500	.2702	.9357	.9219	.9125	.9070	.9053
.625	.2516	.9316	.9191	.9107	.9058	.9043
.750	.2545	.9282	.9157	.9073	.9024	.9008
.875	.2787	.9212	.9089	.9005	.8955	.8940
1.000 (EXIT)	.3245	.9331	.9331	.9331	.9331	.9331

FIGURE 16(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .190346+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .865213+04 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9777	.9777	46.776074	.00000
.125	.99981	.9952	.9889	.9453	.9453	91.621171	.14379
.250	.99962	.9912	.9821	.9446	.9446	78.693769	.30749
.375	.99942	.9877	.9736	.9392	.9392	72.155310	.44290
.500	.99923	.9844	.9680	.9357	.9357	67.887362	.57417
.625	.99904	.9815	.9603	.9316	.9316	60.128966	.69518
.750	.99885	.9787	.9564	.9282	.9282	59.147844	.80515
.875	.99867	.9759	.9488	.9212	.9212	57.910906	.91549
1.000 (EXIT)	.99848	.9745	.9446	.9331	.9331	24.112062	1.00000

ELAPSED TIME IS .2100 HR
RELATIVE TIME IS 54.8908 **IN ORBIT** 107 INTEGR. STEPS

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1081+05 BTU/HR
COND. FROM MANIFOLDS, CONDMF = .2873+03 BTU/HR

INCIDENT SOLAR FLUX, QSOLR = .4326+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .9903+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.9825+03 BTU/HR

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AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.4659	.9763	.9763	.9763	.9763	.9763
.125	.3485	.9402	.9212	.9079	.9002	.8976
.250	.2736	.9401	.9236	.9123	.9057	.9036
.375	.2620	.9337	.9182	.9077	.9015	.8995
.500	.2510	.9297	.9149	.9048	.8989	.8970
.625	.2295	.9247	.9113	.9022	.8969	.8953
.750	.2309	.9206	.9071	.8979	.8925	.8908
.875	.2552	.9118	.8983	.8889	.8834	.8817
1.000 (EXIT)	.3023	.9252	.9252	.9252	.9252	.9252

FIGURE 16(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=TO H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .181485+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .953815+04 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9763	.9763	49.157877	.00000
.125	.99981	.9947	.9878	.9402	.9402	98.755130	.14067
.250	.99962	.9905	.9807	.9401	.9401	84.352570	.30112
.375	.99942	.9867	.9713	.9337	.9337	78.174984	.43370
.500	.99923	.9831	.9654	.9297	.9297	74.254160	.56407
.625	.99904	.9799	.9567	.9247	.9247	66.467727	.68532
.750	.99885	.9768	.9525	.9206	.9206	66.269156	.79686
.875	.99866	.9736	.9438	.9118	.9118	66.394603	.91070
1.000 (EXIT)	.99848	.9719	.9389	.9252	.9252	28.582312	1.00000

ELAPSED TIME IS .2800 HR
RELATIVE TIME IS 73.1878 **IN ORBIT** 136 INTEGR. STEPS

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1059+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .2989+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .4326+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .7787+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.4030+03 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.4658	.9758	.9758	.9758	.9758	.9758
.125	.3461	.9382	.9187	.9051	.8972	.8946
.250	.2695	.9384	.9216	.9101	.9033	.9012
.375	.2570	.9315	.9158	.9049	.8986	.8966
.500	.2451	.9274	.9123	.9019	.8958	.8939
.625	.2224	.9220	.9083	.8989	.8935	.8917
.750	.2230	.9176	.9037	.8941	.8886	.8868
.875	.2472	.9080	.8939	.8841	.8783	.8765
1.000 (EXIT)	.2947	.9219	.9219	.9219	.9219	.9219

FIGURE 16(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .177966+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .989009+04 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9758	.9758	50.129854	.00000
.125	.99981	.9946	.9873	.9382	.9382	101.470659	.13955
.250	.99961	.9903	.9802	.9384	.9384	86.378242	.29864
.375	.99942	.9863	.9704	.9315	.9315	80.419735	.42994
.500	.99923	.9826	.9644	.9274	.9274	76.643045	.55984
.625	.99904	.9793	.9553	.9220	.9220	68.930267	.68103
.750	.99885	.9760	.9510	.9176	.9176	69.137488	.79315
.875	.99866	.9727	.9418	.9080	.9080	70.083364	.90853
1.000 (EXIT)	.99848	.9708	.9367	.9219	.9219	30.468460	1.00000

ELAPSED TIME IS .3150 HR
RELATIVE TIME IS 82.3363 **IN ORBIT** 151 INTEGR. STEPS

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, TOQ = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1056+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .3020+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .4326+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .6522+01 BTU/(HR SQ FT) 78
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.2744+03 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.4664	.9756	.9756	.9756	.9756	.9756
.125	.3461	.9377	.9180	.9044	.8954	.8937
.250	.2690	.9380	.9211	.9095	.9027	.9005
.375	.2564	.9309	.9151	.9042	.8979	.8958
.500	.2442	.9268	.9116	.9011	.8950	.8931
.625	.2211	.9213	.9074	.8980	.8925	.8908
.750	.2216	.9168	.9028	.8931	.8875	.8857
.875	.2457	.9069	.8927	.8828	.8770	.8751
1.000 (EXIT)	.2934	.9211	.9211	.9211	.9211	.9211

FIGURE 16(A) CONCLUDED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .177034+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .998328+04 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9756	.9756	50.420656	.00000
.125	.99981	.9945	.9871	.9377	.9377	102.200647	.13930
.250	.99961	.9902	.9800	.9380	.9380	86.914325	.29805
.375	.99942	.9862	.9701	.9309	.9309	81.018184	.42902
.500	.99923	.9825	.9642	.9268	.9268	77.254283	.55679
.625	.99904	.9791	.9549	.9213	.9213	69.565755	.67993
.750	.99885	.9759	.9506	.9168	.9168	69.883926	.79218
.875	.99866	.9724	.9413	.9069	.9069	71.081735	.90794
1.000 (EXIT)	.99848	.9706	.9361	.9211	.9211	30.978268	1.00000

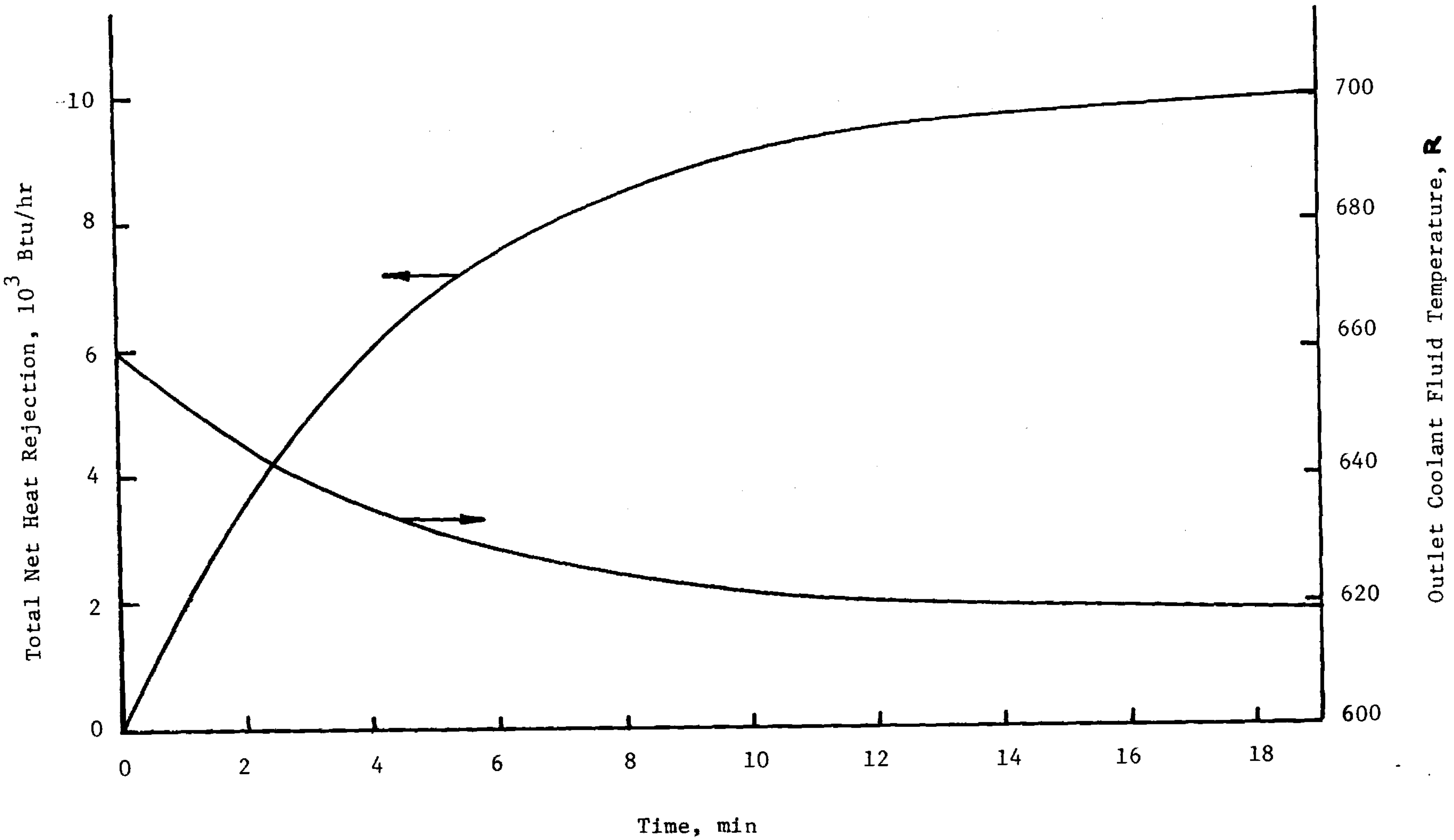

Fig. 16(b) System Response For Orbital Mission-Heat Rejection And Outlet Fluid Temperature

d. Steady State Environment

(i) Description of Environment

Program output has been produced for steady state system performance to a time invariant environmental conditions. The entire radiator system is initially assumed to be at a uniform temperature of 200°F (TI = 659.67R). The integration process is started and it proceeds until steady state operation of the system is achieved. The environmental conditions during the integration process remain constant. For the output of Figure 17, incident radiant flux values were read in from cards according to the format described in section A.3(d). These flux values were 100 Btu/hr. ft.^{2} for solar irradiation, 2.0 Btu/hr. ft.^{2} for earth albedo. There was assumed to be no infrared earth irradiation. There was no aerodynamic heating of the radiator panel. All other input parameters are the same as those used for program output during ascent (see section A.5(a)).

(ii) System Response

The response of the radiator system during the period leading to steady state operation is shown in Figure 17. Figure 17(a) shows the input parameters and a selected number of output listings of the system performance. Figure 17(b) graphically summarizes the resulting outlet coolant fluid temperature and the total heat rejection of the radiator system as the system approaches steady state operation.

```
$QNML
ITAPE    =            +0
ICASE    =            +0
NTM      =            +4
TO       =  .00000000E+00
PHN      =  .00000000E+00

$END
$TUBE
DITBI    =  .25000000E+00
STBI     =  .10000000E+00
XL       =  .12000000E+02
RHOTBI   =  .16859200E+03
MZ       =            +5
NRTBI    =            +3
NTBS     =           +10

$END
$FLOW
MDOTI    =  .50000000E+03
TO       =  .65967000E+03
PO       =  .86400000E+04

$END
$FIN
NX       =            +5
SROOTI   =  .50000000E-01
HFNI     =  .60000000E+01
STIPI    =  .50000000E-01
RHOFNI   =  .16859200E+03
STAGX    =  .20000000E+02
VERTA    =  .10000000E+02

$END
$PROTLR
NRMP     =            +3
RHOMPI   =  .16859200E+03
RHOMET   =  .50000000E+00
VELM     =  .65600000E+05
TAU      =  .36500000E+04
PROB     =  .99000000E+00
ALPHA    =  .18800000E-09
BTA      =  .12130000E+01
GAMMA    =  .15000000E+01
PHI      =  .50000000E+00
THETA    =  .66666700E+00
ATK      =  .17500000E+01
AN       =  .10000000E+01

$END
$MANIFD
AMAN     =  .43000000E+02

$END
$RUNOPT
MSTOTR   =            +1
```

Figure 17(a) System Response for Steady State Environment
Program Output

```
DTWRTE  =     .33333000E-01
TEND    =     .00000000E+00
ALIMIT  =     .50000000E-04
RLIMIT  =     .10000000E-04
TI      =     .65967000E+03
LIMWRT  =               +25
NCONV   =                +0
LTT     =                +0
LFLD    =                +1
LTS     =                +0

$END
```

FIGURE 17(A) CONTINUED

```
INITIAL LINE CONDITIONS
******* **** **********
             (ALL QUANTITIES ARE NORMALIZED)
                                                                                FLUID                WALL
    PT.NO.  POSITION             PRESSURE           VELOCITY          TEMPERATURE          TEMPERATURE
               Z                     P                  W                  T                   TWI

       1      .000               1.000000           1.000000           1.000000            1.000000
       2      .250                .999621           1.000001           1.000000            1.000000
       3      .500                .999241           1.000001           1.000000            1.000000
       4      .750                .998862           1.000001           1.000000            1.000000
       5     1.000                .998483           1.000002           1.000000            1.000000

INLET PRESSURE   PO  =    8640.000  LBF/SQ.FT
REF.  VELOCITY   WO  =      .87128  FT/SEC
REF. TEMPERATURE TOO =     659.670  R

      REYNOLDS NO    =              .30017+04
      PRANDTL  NO    =              8.628066
      DELTA          =               .001736
      REL.PRESSURE IS               .391534+04

INIT. NUSSELT NO. NU =              .201856+02
WALL BIOT NO.     BI =              .485314-02

          SYSTEM PARAMETERS
          ****** **********

TUBE LENGTH ,                      XL =     12.000 FT
     INTERNAL DIAMETER ,         DITB =       .250 IN
     WALL THICKNESS ,             STB =       .100 IN
     MATERIAL                           ALUMINUM
     MASS    (ALL TUBES) ,        MTB =    15.4480 LBM
     NUMBER OF TUBES,            NTBS =         10

FIN  HEIGHT ,                     HFN =      6.000 IN
     THICKNESS AT ROOT ,        SROOT =       .050 IN
     THICKNESS AT TIP ,          STIP =       .050 IN
     MATERIAL                           ALUMINUM
     MASS (ALL FINS) ,            MFN =    84.2960 LBM
     NO. OF FIN SIDES RADIATING    =            1

COOLANT FLUID IS                        SILICONE OIL
     MASS (IN ALL TUBES) ,        MFL =    19.1289 LBM

 PROTECTION LAYER THICKNESS,  SMP =         .011 IN
     MASS,                        MMP =      2.038 LBM
     MATERIAL IS                        BERYLLIUM

TOTAL MASS (EXCL. MANIFLD.) MTOT =   120.9104 LBM
TOTAL AREA (SINGLE NORMAL PROJECTION) ,
                         ATOT =   124.5000 SQ FT
```

FIGURE 17(A) CONTINUED

ELAPSED TIME IS .0000 HR
RELATIVE TIME IS .0000 **IN ORBIT** 1 INTEGR. STEPS

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .3288+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .0000 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.3288+05 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.8477	1.0000	1.0000	1.0000	1.0000	1.0000
.250	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
.500	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
.750	.8436	1.0000	1.0000	1.0000	1.0000	1.0000
1.000 (EXIT)	.8477	1.0000	1.0000	1.0000	1.0000	1.0000

FIGURE 17(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .276866+05 BTU/HR
INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .498047-01 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TF (TEMPERATURES)	WALL TWI (TEMPERATURES)	PROTECT. LAYER TMP (TEMPERATURES)	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	1.0000	1.0000	.000000	.00000
.250	.99962	1.0000	1.0000	1.0000	1.0000	.000277	.10085
.500	.99924	1.0000	1.0000	1.0000	1.0000	.000415	.33176
.750	.99886	1.0000	1.0000	1.0000	1.0000	.000519	.63619
1.000 (EXIT)	.99848	1.0000	1.0000	1.0000	1.0000	.000588	1.00000

ELAPSED TIME IS .1000 HR
RELATIVE TIME IS 26.1382 **IN ORBIT** 52 INTEGR. STEPS

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1977+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .1545+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.7621+04 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7309	.9669	.9669	.9669	.9669	.9669
.250	.5016	.9203	.8992	.8851	.8770	.8744
.500	.4808	.9091	.8903	.8777	.8704	.8681
.750	.4615	.8974	.8815	.8709	.8647	.8628
1.000 (EXIT)	.5476	.9070	.9070	.9070	.9070	.9070

FIGURE 17(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .156871+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .119996+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9669	.9669	69.442389	.00000
.250	.99962	.9884	.9740	.9203	.9203	112.865777	.27736
.500	.99923	.9788	.9559	.9091	.9091	98.273507	.58267
.750	.99886	.9709	.9354	.8974	.8974	79.855536	.82863
1.000 (EXIT)	.99848	.9668	.9238	.9070	.9070	35.347144	1.00000

ELAPSED TIME IS .2000 HR
RELATIVE TIME IS 52.2765 **IN ORBIT** 79 INTEGR. STEPS

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1740+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .1896+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.2265+04 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7183	.9632	.9632	.9632	.9632	.9632
.250	.4485	.9041	.8798	.8630	.8533	.8501
.500	.4166	.8883	.8657	.8502	.8411	.8381
.750	.3838	.8698	.8501	.8366	.8287	.8261
1.000 (EXIT)	.4785	.8810	.8810	.8810	.8810	.8810

FIGURE 17(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .127453+05 BTU/HR
INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .149414+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9632	.9632	75.726097	.00000
.250	.99961	.9863	.9690	.9041	.9041	133.561531	.25844
.500	.99923	.9745	.9478	.8883	.8883	122.299504	.55811
.750	.99886	.9641	.9208	.8698	.8698	104.992007	.81310
1.000 (EXIT)	.99848	.9585	.9050	.8810	.8810	49.425550	1.00000

ELAPSED TIME IS .3000 HR
RELATIVE TIME IS 78.4147 **IN ORBIT** 104 INTEGR. STEPS

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION

REFERENCE TEMPERATURE, T00 = 659.670 R
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1685+05 BTU/HR
COND. FROM MANIFOLDS, CONDMF = .1986+03 BTU/HR

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.9773+03 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7158	.9624	.9624	.9624	.9624	.9624
.250	.4374	.9005	.8755	.8582	.8481	.8448
.500	.4025	.8836	.8600	.8437	.8342	.8311
.750	.3645	.8625	.8417	.8273	.8189	.8162
1.000 (EXIT)	.4617	.8743	.8743	.8743	.8743	.8743

FIGURE 17(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .120168+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .156699+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TF (TEMPERATURES)	WALL TWI (TEMPERATURES)	PROTECT. LAYER TMP (TEMPERATURES)	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9624	.9624	76.930037	.00000
.250	.99961	.9858	.9678	.9005	.9005	137.760096	.25316
.500	.99923	.9735	.9462	.8836	.8836	128.067226	.55047
.750	.99886	.9625	.9173	.8625	.8625	112.156114	.80811
1.000 (EXIT)	.99848	.9565	.9003	.8743	.8743	53.326069	1.00000

ELAPSED TIME IS .4000 HR
RELATIVE TIME IS 104.5529 **IN ORBIT** 130 INTEGR. STEPS

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1671+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .2010+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.6569+03 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7152	.9622	.9622	.9622	.9622	.9622
.250	.4348	.8997	.8745	.8571	.8469	.8436
.500	.3993	.8825	.8587	.8422	.8326	.8294
.750	.3595	.8607	.8395	.8249	.8163	.8135
1.000 (EXIT)	.4574	.8725	.8725	.8725	.8725	.8725

FIGURE 17(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .118339+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .158528+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9622	.9622	77.176887	.00000
.250	.99961	.9857	.9675	.8997	.8997	138.666939	.25172
.500	.99923	.9733	.9458	.8825	.8825	129.416553	.54823
.750	.99886	.9621	.9165	.8607	.8607	114.102509	.80655
1.000 (EXIT)	.99848	.9560	.8992	.8725	.8725	54.379859	1.00000

ELAPSED TIME IS .5000 HR
RELATIVE TIME IS 130.6912 **IN ORBIT** 157 INTEGR. STEPS

02

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION
****

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1668+05 BTU/HR ,
COND. FROM MANIFOLDS, CONDMF = .2017+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.5757+03 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7150	.9622	.9622	.9622	.9622	.9622
.250	.4342	.8994	.8742	.8568	.8466	.8433
.500	.3985	.8822	.8584	.8419	.8322	.8290
.750	.3582	.8602	.8390	.8243	.8156	.8128
1.000 (EXIT)	.4564	.8721	.8721	.8721	.8721	.8721

FIGURE 17(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER
****

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .117874+05 BTU/HR

INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .158993+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9622	.9622	77.232511	.00000
.250	.99961	.9857	.9674	.8994	.8994	138.877901	.25135
.500	.99923	.9732	.9457	.8822	.8822	129.726835	.54762
.750	.99886	.9620	.9163	.8602	.8602	114.610315	.80610
1.000 (EXIT)	.99848	.9558	.8989	.8721	.8721	54.654328	1.00000

ELAPSED TIME IS .6000 HR
RELATIVE TIME IS 156.8294 **IN ORBIT** 184 INTEGR. STEPS

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION

REFERENCE TEMPERATURE, T00 = 659.670 R ,
REF. RADIANT HEAT FLUX
PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1667+05 BTU/HR ,
COND. FROM MANIFOLDS. CONDMF = .2018+03 BTU/HR ,

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.5547+03 BTU/HR

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7150	.9622	.9622	.9622	.9622	.9622
.250	.4340	.8994	.8741	.8567	.8465	.8432
.500	.3983	.8822	.8583	.8418	.8321	.8289
.750	.3579	.8601	.8388	.8241	.8155	.8127
1.000 (EXIT)	.4561	.8720	.8720	.8720	.8720	.8720

FIGURE 17(A) CONTINUED

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .117753+05 BTU/HR
INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .159114+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9622	.9622	77.246378	.00000
.250	.99961	.9857	.9674	.8994	.8994	138.930130	.25127
.500	.99923	.9732	.9457	.8822	.8822	129.798357	.54747
.750	.99886	.9620	.9162	.8601	.8601	114.739276	.80599
1.000 (EXIT)	.99848	.9558	.8988	.8720	.8720	54.722584	1.00000

ELAPSED TIME IS .6183 HR
RELATIVE TIME IS 161.6107 **IN ORBIT** 188 INTEGR. STEPS

FIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT REJECTION

REFERENCE TEMPERATURE, T00 = 659.670 R
REF. RADIANT HEAT FLUX PER UNIT AXIAL LENGTH, QREF = .3246+04 BTU/(HR FT),
TOT. RADIANT REJECTION QTOT = .1667+05 BTU/HR
COND. FROM MANIFOLDS, CONDMF = .2019+03 BTU/HR

INCIDENT SOLAR FLUX, QSOLR = .1000+03 BTU/(HR SQ FT)
INCIDENT INFRARED FLUX, QIRED = .2000+01 BTU/(HR SQ FT)
AERODYN. HEATING POWER, QCONV = .0000 BTU/HR
ENERGY STORAGE RATE, STORG = -.5533+03 BTU/HR

FIGURE 17(A) CONCLUDED

AXIAL DIST. Z	RELATIVE RAD. HEAT REJECTION Q	RELATIVE TEMPERATURE OF FIN, T — DISTANCE NORMAL TO FLOW DIRECTION X: .00000	.25000	.50000	.75000	1.00000
.000	.7150	.9622	.9622	.9622	.9622	.9622
.250	.4340	.8994	.8741	.8567	.8465	.8432
.500	.3983	.8822	.8583	.8418	.8321	.8289
.750	.3579	.8600	.8388	.8241	.8155	.8126
1.000 (EXIT)	.4561	.8720	.8720	.8720	.8720	.8720

FLUID PROPERTIES AND SURFACE TEMPERATURE OF METEOROID PROTECTION LAYER

REFERENCE TEMPERATURE, T00 = 659.670 R
REFERENCE PRESSURE, P00 = 8640.000 LBF/SQ.FT
REFERENCE VELOCITY, W00 = .871 FT/SEC
COOLANT POWER, INLET AT T=T0 H0 = .276867+05 BTU/HR
EXIT CURRENTLY EI = .117746+05 BTU/HR
INLET CURRENTLY HI = .276867+05 BTU/HR
TOT. REJECTION DH = .159121+05 BTU/HR

AXIAL DIST.	PRESSURE P	VELOCITY W	FLUID TEMPERATURES TF	WALL TEMPERATURES TWI	PROTECT. LAYER TEMPERATURES TMP	ENTHALPY REJECTION PER UNIT TUBE LENGTH BTU/(HR FT)	ENTHALPY REJECTION FRACTION OF TOTAL
.000	1.00000	1.0000	1.0000	.9622	.9622	77.247403	.00000
.250	.99961	.9857	.9674	.8994	.8994	138.934032	.25126
.500	.99923	.9732	.9457	.8822	.8822	129.805758	.54745
.750	.99886	.9620	.9162	.8600	.8600	114.752011	.80597
1.000 (EXIT)	.99848	.9558	.8988	.8720	.8720	54.731251	1.00000

STEADY STATE IS REACHED

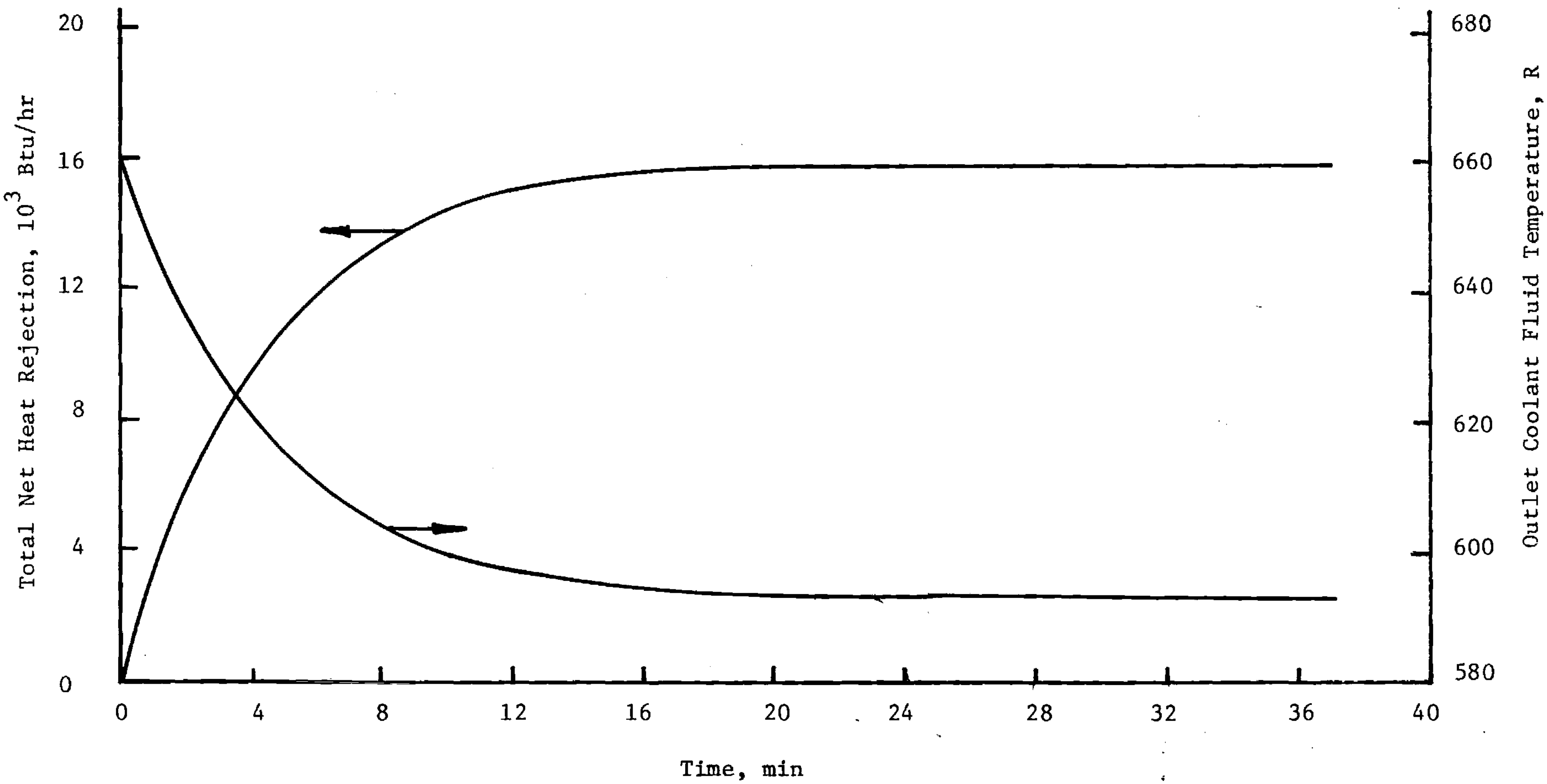

Fig. 17(b) System Response for Steady State Environment-System Heat Rejection And Outlet Fluid Temperature

B. Program Description

1. Structure

The program structure is dictated by the calling sequence of the Runge-Kutta-Simpson integration procedure (see Section III-2 of the System Analysis Manual). The Source Deck consists of two parts. The first part is referred to as the Permanent Part and the second part is called the Selective Part. The Input Data Set follows the Selective Part.

a. The Permanent Part

The Permanent Part requires no attention from the user unless he plans major program modifications such as consideration of geometrical configurations other than the one considered on the present analysis. The Permanent Part contains the first 42 program units.

b. The Selective Part

The Selective part contains the options for selection of system materials. It is assembled from case to case by the user in accordance with his choice of the coolant fluid material, flow channel material, meteoroid protection layer material, fin panel material and thermal control coating material. There are always 20 program units in the Selective Part.

c. The Input Data Set

The Input Data Set follows immediately after the Source Deck. As discussed in Section A-3 the Data Set consists of six groups that specify the non-symmetrical panel conditions, ascent and reentry profiles, the irradiation on the panel, inlet coolant fluid conditions, system specifications and finally the program options. These separate data units are arranged in an order of increasing possibility of input changes so that data units most likely to be changed are at the end of the Data Set.

2. Fastrand Execution

A run procedure was written for the purpose of entering the entire program, including property subprograms, on FASTRAND drums and collecting, or mapping, the program into convenient elements. The elements are chosen so that they form commonly used groups of subprograms which then may be selectively collected into a complete program. The advantages of this technique are the significant reduction in the compilation and collection time and the elimination of submitting the program in card form.

The entire program is mapped into two basic elements: the permanent element and the property elements. The permanent element (called PERM) consists of all subroutines listed in the permanent part of the program; the property elements consist of the material properties of the surface coating, fin material, tube material, meteoroid protection material, and coolant fluid.

Each property element has a unique name. The first two letters of the name are a prefix which indicates the function of the particular material. For example, a property element starting with the prefix CF indicates that those properties to be used for the coolant fluid. The remaining letters of the element name are a suffix which describes the particular material to be used. For example, the suffix HE indicates the material helium. The prefix-suffix combination CFHE, therefore, denotes the coolant fluid of helium.

The sixteen names designating the permanent part of the program and the property elements are as follows:

i) Permanent Elements

1. Element PERM contains all subroutines in the permanent part of the program. (See Part B.3 a through g)

ii) Property Elements

A. Coolant Fluid Properties (Prefix CF)

2. Element CFHE contains all helium properties
3. Element CFSIL contains all silicon oil properties
4. Element CFNAK contains all NaK properties

5. Element CFFC43 contains all properties of the 3-M fluorochemical liquid FC43
6. Element CFFC75 contains all properties of the 3-M fluorochemical liquid FC75

B. Fin Properties (Prefix FN)

7. Element FNAL contains all aluminum properties
8. Element FNCU contains all copper properties
9. Element FNBR contains all beryllium properties

C. Tube Properties (Prefix TB)

10. Element TBAL contains all aluminum properties
11. Element TBCU contains all copper properties
12. Element TBBR contains all beryllium properties

D. Meteoroid Protection Properties (Prefix MP)

13. Element MPAL contains all aluminum properties
14. Element MPCU contains all copper properties
15. Element MPBR contains all beryllium properties

E. Surface Coating Properties (Prefix SC)

16. Element SCZ93 contains all zinc oxide coating (Z93) properties

a. Control Statements

The run deck consists of the following control statements:

The catalogue card

@ CAT,P NASA.,F2

is used to create a file, called here NASA. This card is to be used only the first time the FASTRAND program is run. It must be omitted when subsequent runs are made because the file NASA should be created only once.

The assign card

@ ASG,AX NASA.

is used to name an external file which has been previously catalogued and to cause its assignment to the run. The option A specifies that the file is currently catalogued and the option X specifies that the run is to have exclusive use of the file until the run terminates so that no other run may interfere with the program operation.

The use card

@ USE N.,NASA.

allows the user to refer to the previously catalogued file called NASA by the single letter N. The abbreviated file name will save a great deal of card punching for the subsequent portions of the run.

The Fortran compiler cards, one of which would be

@ FØR,IS N.MAIN

creates Fortran symbolic and relocatable elements both called MAIN which are to be entered into the file NASA. The I option causes the insertion of the element MAIN and the S option produces a listing of the element. There must be a FØR card for each subprogram that is to be entered into the file NASA.

After all of the subprograms have been filed, they are mapped into separate elements. This is achieved by the MAP and IN card.

The MAP cards, one of which would be

@ MAP,ISR ,N.PERM

specifies that the collector should combine a set of relocatable elements from the file NASA into a single relocatable element called PERM. There must be a MAP card for each program element that the user expects to utilize during program operation. A listing of these seventeen elements is given at the beginning of this section.

Following each MAP card is a list of the separate subprograms that are to be placed in the element declared by the MAP card. The placing of each subprogram into the element is achieved by an IN card.

The IN card, one of which would be

IN N.MAIN

places the element MAIN from the file NASA in the element name declared by the previous MAP statement. There must be an IN card for each program element that is to be entered into the element declared by the previous MAP statement.

As an example, if the user wishes to collect the subprograms called AA, BB and CC which are located in the file NASA and place them in an element called ELEM, the proper cards would be:

```
@ MAP,ISR ,NASA.ELEM
IN NASA.AA
IN NASA.BB
IN NASA.CC
```

It is necessary to place a define card at the end of each mapped element.

A define card, one of which could be

DEF THCFN, DTHCFN, CPFN

is used to list those external definitions to be retained by the resulting relocatable element. The DEF statement causes the collector to construct a table defining the entry points to the element. There should be a DEF statement following each MAP card which declares the entry point to each element collected by the MAP card.

b. Input Data

The runstream described above enters all subprograms into the file called NASA and then subdivides the program into convenient groupings of elements. Once this run has been made, it becomes a relatively simple task to collect and run a typical system simulation. As an example, assume the user wishes output for a radiator system consisting of an aluminum fin, copper tube, beryllium meteoroid protection layer, silicon oil coolant fluid and Z93 surface coating. Assuming the user has previously declared the file NASA and he has mapped the sixteen elements discussed above, then this combination of materials could be mapped into an absolute element called VER1 by the runstream consisting of

(Run cards appropriate to the users system)

```
@ ASG,AX NASA.
@ USE N.,NASA.
@ MAP,IS ,N.VER1
IN N.PERM
```

```
IN N.FNAL
IN N.TBCU
IN N.MPBR
IN N.CFSIL
IN N.SCZ93
END
@ XQT N.VER1
```

This deck must be followed by the data set described in Section A-3.

As a second example, if the user wishes to run the program for a system consisting of an aluminum tube, fin and protection layer with helium coolant fluid and Z93 surface coating the deck would consist of

(Run cards appropriate to the users system)

```
@ ASG,AX NASA.
@ USE N.,NASA.
@ MAP,IS ,N.VER2
IN N.PERM
IN N.FNAL
IN N.TBAL
IN N.MPAL
IN N.CFHE
IN N.SCZ93
END
@ XQT N.VER2
```

This deck must be followed by the data deck described in Section A-3. In this example the element PERM plus the property elements are mapped into an absolute element called VER2. It should be pointed out that once these absolute elements have been mapped they are available for subsequent runs without being re-mapped. In future runs, if VER2 is called upon to be executed, the element consisting of PERM plus is the property elements listed above are automatically used.

3. Description of Program Units

This section describes each subprogram which makes up the Permanent and Selective Part of the program.

The description of each subprogram follows the same format. The name of the subprogram is given and it is categorized as either a FUNCTIØN or SUBRØUTINE subprogram. The argument list is also stated.

The objective of each of the subprograms is stated. All input and output variables in the argument list are defined and units are given for all dimensional input and output quantities.

The calling subprograms and those subprograms called are listed for each program unit.

The program units are subdivided into groups of subprograms each of which has a common overall function. For example, all subprograms that are used for the calculation of the aerodynamic heating of the radiator panel are grouped into a common block of programs. In all, there are 62 program units with 42 units on the permanent part and 20 units in the Selective Part. The Permanent Part contains 42 program units grouped in seven sets from (a) through (g) as follows:

a) the principal integration program set with

1. <u>MAIN</u>, the main program unit which

provides	α)	input and output
	β)	unit conversion
	γ)	computation of design parameters
	δ)	preparations for principal integration,
calls	α)	RKS, DERIVM, CNTLM, for principal integration
	β)	FLSTRT to establish the initial flow field
	γ)	FUNCTIØN subprograms for fluid and structural material properties
	δ)	QINCID, SHAPEF (see group c)
	ε)	mathematical procedure subprograms,

2. <u>SUBRØUTINE DERIVM</u> (Y,DY,TIME) which is called from RKS,

receives	α)	the current system state variables Y
	β)	the current time TIME,
provides	α)	all derivatives of the variables Y with respect to time,
calls	α)	CØNVEC, QRAD
	β)	FLSTRT to establish the flow field
	γ)	FUNCTIØN subprograms for fluid and structural material properties
	δ)	mathematical procedure subprograms,

3. <u>SUBRØUTINE CNTLM</u> (Y,DY,DX,X,NTRY,IFVD) which

is called from		RKS,
receives	α)	all system state variables Y
	β)	their derivatives DY
	γ)	current time X, step size DX,
provides	α)	output during integration
	β)	integration step size control
	γ)	integration termination criteria,
calls	α)	HFL, fluid enthalpy subprogram
	β)	mathematical procedure subprograms,

b) the secondary integration program set, necessary to establish the dynamic fluid flow field, with

4. SUBRØUTINE FLSTRT (RE,PR,DELTA) which

is called from		MAIN,DERIVM,
receives	α)	RE, the mean Reynolds number
	β)	PR, the mean Prandtl number
	γ)	DELTA, the diameter-to-length ratio for the tube,
provides	α)	fluid flow (initial and current) conditions
	β)	table heading for initial conditions,
calls	α)	TRNSPT to compute friction factor and convective film coefficient (in non-dimensional form)
	β)	RKSF, DERIVL, CNTLN
	γ)	fluid flow property subprograms
	δ)	mathematical procedure subprograms,

5. SUBRØUTINE DERIVL (Y,DY,X) which

is called from		RKSF,
receives	α)	local fluid flow variables Y
	β)	position along flow channel axis, X,
provides	α)	spatial derivatives DY of Y,

6. SUBRØUTINE CNTLN (Y,DY,DX,X,NTRY,IFVD) which

is called from		RKSF,
receives	α)	the flow variables Y
	β)	their spatial derivatives DY
	γ)	position X, interval DX along channel axis,
provides	α)	output when initial conditions are established
	β)	termination criteria for RKSF integration,

7. SUBRØUTINE TRNSPT (RE,PRL,DELTA,FR,FNU) which computes non-dimensional friction factor and convective film ooefficient, Eqs. 3.7 through 9 and Eqs. 3.16 through 18, and

is called from		FLSTRT,
receives	α)	Reynolds number RE

β) Prandtl number PRL

γ) diameter-to-length ratio DELTA,

provides α) FR = $4f/\delta$, Eq. 3.32

β) FNU = $4\ N_{Nu}/(\delta\ N_{Re} N_{Pr})$, Eq. 3.37,

c) The program set used to calculate the incident net radiant flux, with,

8. SUBRØUTINE QINCID which

   is called from MAIN,

   receives
   α) MSTØTR control option for simulation of steady state (= 1) or transient (= 2) conditions
   β) NSRD the number of radiator sides that are exposed to the environment
   γ) PHN the angle between the reference used in the MRI file data and the normal to the fin panel,

   provides
   α) data transfer from the MRI Incident Radiation Computer program or card input
   β) averaging of radiant flux over circumference of tube cross-section,

9. SUBRØUTINE SHAPEF which

   is called from MAIN,

   provides exchange function SS as defined by Eq. 6.15, see Appendix D,

10. SUBRØUTINE TRMATX which

    is called from QRAD,

    provides the evaluation of the transfer matrix M_{ij}, defined by Eq. 6.7,

11. SUBRØUTINE EXITAV which

    is called from QRAD,

    provides the evaluation of the excitation vector P_j in Eq. 6.18,

12. SUBRØUTINE ABSØRB which

    is called from QRAD,

    receives
    α) total hemispherical emittance ε, see Eq. 6.5
    β) temperature distributions on the fin and tube surfaces
    γ) exchange function SS

	δ)	functions x_{ij} and x_{ijk} defined by Eqs. 6.10 and 6.11,
provides		adsorptance matrix α_{ij} as defined by Eq. 6.9,
calls	α)	SHAPEF for SS
	β)	EMIT for (T)
	γ)	AVGEMT for x_{ij} and x_{ijk}
	δ)	DEFINT for integration,

13. SUBRØUTINE QRAD which

is called from		DERIVM,
receives	α)	transfer matrix and excitation vector M_{ij} and P_j, respectively,
provides	α)	inversion of transfer matrix
	β)	solution of radiosity equations
	γ)	grid mapping,
calls	α)	TRMATX
	β)	EXITAV
	γ)	YINT, INTERP,

d) the program set used to calculate the aerodynamic heating during ascent and reentry, consisting of

14. FUNCTIØN ALTVEL (TIME, IØPTN, AVA, AVR, TA, TR, NA, NR) which interpolates user-supplied altitude and velocity profiles for a given instant, and

is called from		CØNVEC,
receives	α)	current real time, TIME, in seconds, measured from start of transition phase, i.e., ascent: TIME = 0, ALTVEL = AVA (1) reentry: TIME = 0, ALTVEL = AVR (1)
	β)	ordered pairs of time and altitude (TA,AVA) and (TR,AVR) for ascent and reentry, respectively
	γ)	NA and NR, the number of ordered pairs and elements in TA,AVA and TR,AVR, respectively

δ) IØPTN = 0 for ascent
= 1 for reentry,

provides — data interpolation,

calls — YINT for interpolation,

15. SUBRØUTINE ATMØS (ELEV, TATM, CATM) which computes the atmospheric temperature and the speed of sound as functions of altitude and

is called from — CØNVEC,

receives — α) current shuttle elevation, ELEV, in feet

provides — atmospheric temperature, TATM in degrees R and speed of sound, CATM, in ft/sec,

calls — YINT for interpolation, PØLY for evaluation of polynomials,

16. SUBRØUTINE REFP (ELEV, REFTP, REFPR, REFVIS, REFRHØ, REFK, REFCP, REFGAM) which computes the atmospheric air properties as a function of elevation and of high speed reference temperature and

is called from — CØNVEC,

receives — α) current orbiter elevation, ELEV, in feet

β) current high speed reference temperature REFTP, in degrees R,

provides — atmospheric Prandtl number REFPR (dimensionless), dynamic viscosity REFVIS in lbm/(ft sec), density REFRHØ in lbm/ft^3, thermal conductivity REFK in Btu/(sec ft R), specific heat at constant pressure REFCP in Btu/(lbm/R) and the ratio of specific heats REFGAM (dimensionless),

calls — α) YINT for interpolation

β) PØLY for polynomial expansion,

17. SUBRØUTINE NUS (MACHNØ, TATM, CATM, TIN, PRATM, VISATM, RHØATM, STAGX, VERTX, NSRAD, NUS1) which provides a single Nusselt number for the calculation of the aerodynamic heating of the orbiter radiator system at the current time and

is called from — CØNVEC,

receives — α) current orbiter Mach number MACHNØ (dimensionless)

β) current atmospheric temperature TATM, in degrees R

γ) current atmospheric velocity of sound, CATM, in ft/sec

ε) temperature of the coolant fluid at the inlet plane TIN, in degrees R

ζ) atmospheric Prandtl number PRATM, evaluated at the high speed reference temperature (dimensionless)

η) atmospheric density RHØATM, evaluated at the high speed reference temperature in lbm/ft^3

θ) distance from the stagnation point on the shuttle vehicle to the midpoint of the radiator panel measured along a streamline, STAGX, in feet

ι) overall dimension of the radiator panel measure in a direction parallel to the acceleration of gravity, VERTX, in feet

κ) integer value indicating number of non-adiabatic sides of the radiator panel, NSRAD, i.e., NSRAD = 1 for single non-adiabatic surface or NSRAD = 2 for both sides of radiator being non-adiabatic,

provides — mean Nusselt number NUS1, for meteoroid layer and fin at current orbiter elevation during either ascent or reentry (dimensionless),

calls — YINT for interpolation,

18. <u>SUBROUTINE CØNVEC</u> (TIME) which computes normalized aerodynamic heating of fin and meteoroid protection layer for both ascent and reentry phases of orbiter operation and

is called from — DERIVM,

receives — α) current real time TIME, in seconds, measured from start of transition phase; i.e., TIME must be measured with respect to same reference point as user supplied time arrays in FUNCTIØN ALTSH and VELSH,

provides — normalized convective flux from fin surface CØNFN (I,J), and from meteoroid protection surface CØNMP (I),

calls — α) ALTVEL for altitude and velocity of orbiter

β) ATMØS for atmospheric properties

γ) REFP for atmospheric properties evaluated at high speed reference temperature δ) YINT for interpolation

ε) NUS for Nusselt number,

19. FUNCTIØN CPAIR (T) which computes the specific heat at constant pressure for atmospheric air and

is called from	ATMØS, REFTP and CØNVEC,
receives	absolute temperature T in R,
provides	specific heat at constant pressure in Btu/lbmR,
calls	PØLY for polynomial expansion,

20. FUNCTIØN ENTAIR (T) which computes the enthalpy of atmospheric air and

is called from	CØNVEC,
receives	absolute temperature T in R,
provides	enthalpy in Btu/lbm,

21. FUNCTIØN TNH (ENT) which computes the temperature of atmospheric air for a given enthalpy and

is called from		CØNVEC,
receives		enthalpy ENT in Btu/lbm,
provides		absolute temperature in R,
calls	α)	CPAIR for the specific heat at constant pressure of atmospheric air
	β)	ENTAIR for the enthalpy of air,

e) the program to compute the thickness of the meteoroid protection layer

22. FUNCTION TK (GAMMA, A, BETA, DENSM, THETA, PHI, AN ALPHA, VELM, PØ, TAU, DENST, W, TNN, AMAN, TIN, RØUT) which computes the thickness of the meteoroid protection layer for given environmental conditions, tube and manifold areas, experimental constants and protection layer properties and

is called from		MAIN,
receives	α)	nondimensional experimental constant, GAMMA, see Eq. 8.9

β) nondimensional experimental constant A, see Eq. 8.9

γ) nondimensional constant which relates meteoroid flux to mass, BETA

δ) density of the meteoroid particle, DENSM, in gm/cm^3

ε) nondimensional experimental constant THETA, see Eq. 8.9

ζ) nondimensional experimental constant PHI, see Eq. 8.9

η) nondimensional constant AN, used to describe penetration depth as a function of angle of incidence of meteoroid particle

θ) velocity of meteoroid particle relative to radiator panel, VELM, in ft/sec

ι) probability of no damage caused by impact of meteoroid, PØ

κ) time TAU, the radiator panel is exposed to meteoroid environment, in days

λ) density of protection material DENST, in lbm/ft^3

μ) axial length of single flow channel exposed to meteoroid environment, W, in inches

ν) integer number of flow channels, TNN,

ξ) area of the manifold that is exposed, AMAN, in ft^2

ϕ) temperature of coolant fluid at inlet plane of flow channel, TIN, in degrees R

π) outside radius RØUT of the unprotected flow channel, in inches,

provides — meteoroid protection thickness TK, in inches,

calls — ELAS for modulus of elasticity of protection material,

f) the program set which calculates the location of the adiabatic plane between two flow channels under conditions of non-symmetrical loading of the tubes and for curved radiator panels, consisting of

23. SUBRØUTINE SHADE which zeros those elements in the array Q which correspond to portions of the radiator panel that do not receive solar, albedo and planetary irradiation and

is called from TCALC and QINCID,

receives

α) NS, number of flat sides to the polygon used as a reference body by MRI program for calculating incident radiant flux

β) radiant flux array Q in Btu/hr ft^2. Array must have NS or greater values,

provides zeros in part of the Q array which correspond to fin elements in the shade,

24. SUBRØUTINE TCALC which calculates the equivalent sink temperatures from incident flux data and,

is called from MAIN,

receives NTF the number of flat fin segments.

provides TSTAR the equivalent sink temperature in R,

calls SHADE for incident flux data,

25. SUBRØUTINE EFFICY which evaluates the one-dimensional fin efficiency and its derivative as a function of the fin base temperature and

is called from TTIPS,

receives

α) the dimensionless conductance parameter NC

β) the derivative of the conductance parameter with respect to the base temperature NCPR in R^{-1}

γ) the ratio of the sink to base temperature TSØTB

δ) the fin base temperature TB in R,

provides

α) the fin efficiency ETA

β) the derivative of the fin efficiency with respect to the base temperature ETAPR in R^{-1},

calls PØLY for polynomial expansion,

26. SUBRØUTINE TTIP which computes the tip temperature of a one-dimensional fin and

is called from ADIABH,

receives

α) the dimensionless conductance parameter NC β) the ratio of the sink to base temperature TSØTB,

provides — the ratio of the difference between the fin tip temperature and sink temperature to the difference between the base and sink temperature,

calls — PØLY for polynomial expansion,

27. FUNCTIØN NUSA which evaluates the Nusselt number for the coolant fluid flow for both laminar and turbulent flow and

is called from — ADIABH and TTIPS,

receives
- α) the Reynold number for the fluid REY
- β) the Prandtl number for the fluid PR
- γ) the ratio of the internal tube diameter to tube length DØL,

provides — the fluid Nusselt number,

28. SUBRØUTINE TTIPS which uses the Newton-Raphson method to numerically solve for the base temperature of the one-dimensional fin and

is called from — ADIABH,

receives
- α) the integer IT used to specify the tube number for which the fin tip temperatures are calculated. Numbering system is consistent with the input parameters TIN (inlet temperature), PIN (inlet pressure), T (fin thickness), AL (tube length) and M (mass flow rate)
- β) the integer ITST which designates the sink temperature data stored in the array TSTAR
- γ) the distance H1 to the adiabatic plane for the fin attached to the left of the tube number IT, in inches
- δ) the distance H2 to the adiabatic plane for the fin attached to the right of the tube number IT, in inches,

provides
- α) the adiabatic plane temperature for the fin attached to the right of tube IT in R
- β) the adiabatic plane temperature for the fin attached to the left of tube IT in R,

calls
- α) NUS for the coolant fluid Nusselt number
- β) EFFICY for fin efficiency
- γ) TTIP for the fin tip temperature,

29. SUBRØUTINE ADIABH which determines the position of the adiabatic planes so that there is a continuity in adiabatic plane temperature of the one-dimensional fin and so that the heat convected from the fluid equals the heat radiated from the fin and

is called from		MAIN,
receives		the integer ITST which designates sink temperature data stored in the array TSTAR,
provides		printout of table headings and system parameters when radiator is non-symmetrically loaded and diagnostic printout if distance to adiabatic plane exceeds the spacing between the tubes. For this case one tube is transferring heat to the fin while the adjacent tube is gaining heat. TTIPS also provides the distances to all the adiabatic planes within the non-symmetrical radiator section,
calls	α)	property subroutines for fin and fluid properties
	β)	NUS for the coolant fluid Nusselt number
	γ)	TTIPS for the tip temperature of the fin
	δ)	PDERIV for determination of the elements of the matrix P_{ij}
	ε)	FMINV for matrix inversion,

30. FUNCTIØN PDERIV which calculates the partial derivative $\partial\delta_i/\partial h_j$ (see Section II-14 of the System Analysis Manual) and

is called from		ADIABH,
receives	α)	the integer J denotes the tube under consideration, J = -1 denotes tube IT - 1; J = 0 denotes tube IT and J = +1 denotes tube IT + 1
	β)	the integer IT which specifies the tube number to be considered
	γ)	the integer ITST which designates sink temperature data stored in the array TSTAR,
provides		the partial derivative $\partial h_i/\partial h_j$
calls		TTIPS for evaluation of the temperature at the adiabatic plane,

g) the program set consisting of all the mathematical procedures discussed in detail in Part III of the System Analysis Manual'

31. SUBRØUTINE RKSF (see Section III.15) which

    is called from FLSTRT, for dynamic fluid flow field,
    calls DERIVL, CNTLN,

32. SUBRØUTINE RKS (see Section III.15) which

    is called from MAIN, for principal integration,
    calls DERIVM, CNTLM,

33. FUNCTIØN PØLY (X,A,M) (see Section III.16),

34. FUNCTIØN YINT (X,Y,M,N,P) (see Section III.17),

35. SUBRØUTINE DDX (Y,DY,DX,N),

36. SUBRØUTINE D2DX2 (Y,D2Y,DX,N), (see Section III.18)

37. FUNCTIØN DEFINT (Y,DX,N),

38. SUBRØUTINE FINT (Y,YO,DX,N,F), (see Section III.19)

39. SUBRØUTINE INTERP (NX1,MZ1,XX1,ZZ1,YY1,NX2,MZ2,XX2,ZZ2,YY2) maps a two-dimensional function YY1 from one grid (XX1,ZZ1) onto another grid (XX2,ZZ2) and

is called from		QRAD,
receives	α)	the number of nodal points (NX1,MZ1) of the original grid
	β)	the function YY1
	γ)	the number of nodal points (NX2,MZ2) of new grid,
provides		the function YY2 at the new grid,
calls		YINT,
is restricted to		NX1,MZ1,NX2,MZ2 $\leq$ 10,

40. FUNCTIØN DEFNT serves to integrate by the trapezoidal rule and is used where random error accumulation is more critical than truncation errors, and V accepts through its argument list (Y, DX, N)

α) the array Y of N equally spaced ordinates

β) the interval DX

γ) the integer constant N, representing the number of nodal points.

returns the integral of YCS) as DEFNT.

41. SUBROUTINE MTXINV (N,M) performs two related tasks:

(i) to solve a system of N linear algebraic equations, when M = N + 1,

(ii) to invert an N x N invertible matrix, when M = 2N.

For task (i) it

accepts through CØMMØN TRMTX (k,1) the augmented coefficient matrix (see Chapter III.7). Here k and 1 represent integer constants, k = N, 1 = N + 1.

through the argument list (N,M) the rank N of the coefficient matrix and M = N + 1, two integer constants.

returns the solution in TRMTX (I,J), I = 1, ..., k, J = k.

For task (i) it

accepts through CØMMØN TRMTX (k,1)

the k x k matrix in the first k columns of TRMTX (I,J), I = 1, ..., k; J = 1, ..., k and the k x k identity matrix in the second k columns of TRMTX (I,J) I = 1, ..., k; J = k + 1, ..., 2k. Hence 1 = 2k.

through the argument list (N,M) the rank N of the coefficient matrix and M = 2N, both integer constants.

returns the inverted matrix in the second k columns of TRMTX (I,J), I = 1, ..., k; J = k + 1, ..., 2k.

42. SUBRØUTINE FMINV serves to solve N linear algebraic equations by the method used for SUBRØUTINE MTXINV. It's calling provisions are designed to accommodate the requirements of ADIABH. It

receives, through its argument list (A,X,N,M)

α) the (N x N), invertible coefficient matrix A

β) the know, N-dimensional vector X

γ) the rank (N) of A, an integer constant

δ) $M = N + 1$

where $N \leq 25$

returns the solution $Y = A^{-1}X$ placed in the array X

is called from ADIABH.

The Selective Part contains five groups of thermophysical properties, with the total of 20 program units. Each group constitutes a property package, one each for

(i) the coolant fluid (8 program units)
(ii) the flow channel material (3 program units)
(iii) the meteoroid protection layer (4 program units)
(iv) the fin material (3 program units)
(v) the thermal control coating (2 program units).

The choice of a particular material combination must be reflected in the corresponding data specification of the Input Data Set, (see Section 3f of Chapter A).

a) The coolant property subprogram set consists of eight elements, 43 through 50

43. FUNCTIØN RHØF (P,T) which computes the fluid density RHØF in slug/ft^3 as a function of pressure P in lbf/ft^2, and absolute temperature T in R,

44. FUNCTIØN BETA (RHØ,T) which computes the isobaric expansion coefficient β, Section II.C.11, in 1/R as a function of density RHØ in slug/ft^3, and temperature T in R,

45. FUNCTIØN CAPPA (P,T) which computes the isothermal compressibility, Eq. 11.3, in ft^2/lbf, as a function of pressure P in lbf/ft^2, and temperature T in R,

46. FUNCTIØN CPF (RHØ,T) which computes the specific heat at constant pressure CPF, in Btu/(slug R), as a function of density RHØ in slug/ft^3, and temperature T, in R,

47. FUNCTIØN HFL (RHØ,T) which computes the fluid enthalpy HFL, in Btu/slug, as a function of density RHØ in slug/ft^3, and temperature T, in R,

48. FUNCTIØN VISC (RHØ,T) which computes the fluid dynamic viscosity VISC, in slug/(ft sec) as a function of density RHØ in slug/ft^3, and temperature T, in R,

49. FUNCTIØN THCF (RHØ,T) which computes the fluid thermal conductivity THCF in Btu/(hr ft R) as a function of density RHØ in slug/ft^3, and temperature T, in R,

50. FUNCTIØN PF (RHØ,T) which computes the fluid pressure PF in lbf/ft^2 as a function of density RHØ in slugs/ft^3, and absolute temperature T, in R. For specific details of the coolant fluid properties, see Section II.11 and 12 and Appendix B of the System Analysis Manual.

b) The coolant channel material property subprogram set consists of three elements, 51 through 53.

51. FUNCTIØN THCTB (T) computes the thermal conductivity THCTB in Btu/(hr ft R), of the tube wall material as a function of the absolute temperature T, in R,

52. FUNCTIØN DTHCTB (T) computes the relative change of thermal conductivity k with temperature T, namely $(dk_w/dT)/k_w$ in 1/R, as a function of temperature T, in R,

53. FUNCTIØN CPTB (T) computes the specific heat at constant pressure CPTB, in Btu/(slug R) as a function of T, in R.

For specific details of the coolant channel properties, see Appendix A of the System Analysis Manual.

c) the meteoroid protection layer material properties are coded in a set of four elements, 54 through 57

54. FUNCTIØN THCMP (T),
55. FUNCTIØN DTHCMP (T),
56. FUNCTIØN CPMP (T),
57. FUNCTIØN ELAS (T) computes the modulus of elasticity ELAS in lbf/in^2 as a function of temperature T, in R.

For specific details of the meteoroid protection properties, see Appendix A of the System Analysis Manual.

d) The fin material properties required are coded in three FUNCTIØN subprograms, numbered 58 through 60

58. FUNCTIØN THCFN (T) computes the thermal conductivity THCFN, in Btu/(hr ft R) for the fin material as a function of absolute temperature T, in R,

59. FUNCTIØN DTHCFN (T) computes the relative change of thermal conductivity, namely $(dk_f/dT)/k_f$ in 1/R, as a function of temperature T, in R,

60. FUNCTIØN CPFN (T) computes the specific heat at constant pressure CPFN, in Btu/(slug R) as a function of temperature T, in R.

For specific details of the fin material properties, see Appendix A of the System Analysis Manual.

e) Optical properties of the thermal control coating are coded in two subprograms, numbered 61 and 62

61. FUNCTIØN EMIT (T) computes the total hemispherical emittance in accordance with Eq. 6.5 of the System Analysis Manual as a function of the surface temperature T in R, and is called by ABSØRB and EXITAV,

62. SUBRØUTINE AVGEMT (T,XX,XXX,N) evaluates the expressions for x_{ij} and x_{ijk} given as Eqs. 6.10 and 11 in the System Analysis Manual for N interacting surface elements. It is called by ABSØRB (see program No. 12).

For specific details of surface coating properties, see Appendix C of the System Analysis Manual.

This completes the Source Deck discussion. Recall that the Source Deck composition implies a particular selection of coolant fluid and structural materials.

4. Program Listing

This section contains the entire program listing in alphabetical order of subprogram name.

Labelled common blocks and external program references and printed out prior to the listing of each program unit.

All program units have been documented with comment cards for the convenience of the user.

All program units are summarized in a table of contents which follows the final unit listing. The table of contents lists all program elements as either symbolic or relocatable and it also prints the time and date when the program element was most recently stored on FASTRAND drum.

```
@FOR,S ME*NASA5.ABSORB,ME*NASA5.ABSORB
FOR S9A-07/13/72-20:52:53 (0,)

   SUBROUTINE ABSORB    ENTRY POINT 000552

   STORAGE USED: CODE(1) 000600; DATA(0) 000115; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003    QRD     003721
    0004    ABSRST  000601
    0005    AVGABS  000251

   EXTERNAL REFERENCES (BLOCK, NAME)

    0006    EMIT
    0007    DEFNT
    0010    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001    000032 116G     0001    000042 123G     0001    000062 132G     0001    000065 135G     0001    000067 140G
    0001    000137 152G     0001    000155 161G     0001    000156 164G     0001    000244 174G     0001    000251 177G
    0001    000260 202G     0001    000271 206G     0001    000352 220G     0001    000355 223G     0001    000357 226G
    0001    000430 240G     0004 R 000000 ALPHFN    0004 R 000226 ALPHMP    0000 R 000000 AUX1      0000 R 000005 AUX2
    0000 R 000012 AUX3      0000 R 000017 AUX4      0003 R 003465 CSF       0007 R 000000 DEFNT     0003 R 003464 DXX2
    0003    003472 DXX21    0003    003463 DZMFN    0003 R 003410 EBFN      0003 R 003441 EBMP      0006 R 000000 EMIT
    0004 R 000461 EMITFN    0004 R 000512 EMITMP    0003 R 003467 EXTIFN    0003 R 003471 EXTIMP    0003 R 003466 EXTSFN
    0003 R 003470 EXTSMP    0004    000517 EXTVCT   0000 I 000032 I         0000 I 000037 IL        0000    000057 INJP$
    0000 I 000034 J         0000 I 000040 JL        0000 I 000036 K         0000 I 000043 L         0003    003461 LCT
    0003    003462 LTT      0003    003460 MCVRD    0003 R 003473 SS        0003 R 003670 SSTT      0005 R 000100 TFIN
    0000 R 000035 TFINN     0000 R 000033 TM        0005 R 000244 TPR       0003    000000 TRMTX    0000 R 000041 X
    0005 R 000062 XXFN      0005 R 000000 XXMP      0005 R 000071 XXXFN     0005 R 000031 XXXMP     0003    003446 XX2
    0000 R 000042 Y         0000 R 000026 ZCF       0000 R 000031 ZCM       0000 R 000024 ZF        0000 R 000025 ZFM
    0000 R 000027 ZM        0000 R 000030 ZMM       0003    003453 ZZ2


 00101       1*             SUBROUTINE ABSORB (TO,XCFN,XCMP,XXCFN,XXCMP)
 00101       2*       C
 00101       3*       C   THIS SUBROUTINE COMPUTES :
 00101       4*       C     THE ABSORBTANCE MATRIX REPRESENTING THE MAIN ABSORBTANCE AFTER
 00101       5*       C     INTERNAL INTEGRATIONS
 00101       6*       C
 00103       7*             COMMON /QRD/ TRMTX(30,60),EBFN(5,5),EBMP(5),XX2(5),ZZ2(5),
 00103       8*            1            MCVRD,LCT,LTT,DZMFN,
 00103       9*            2            DXX2,CSF,EXTSFN,EXTIFN,EXTSMP,EXTIMP,DXX21,SS(5,5,5)
 00103      10*            3            ,SSTT(5,5)
 00104      11*             COMMON /ABSRST/ALPHFN(5,5,6),ALPHMP(5,31),EMITFN(5,5),EMITMP(5),
 00104      12*            1              EXTVCT(50)
 00105      13*             COMMON/AVGABS/XXMP(5,5),XXXMP(5,5),XXFN(7),XXXFN(7),
 00105      14*            1             TFIN(10,10),TPR(5)
```

```
00106              DIMENSION AUX1(5),AUX2(5),AUX3(5),AUX4(5)
00106         C
00107              ZF      = EXTSFN+EXTIFN
00110              ZFM     = ZF*(1-XCFN)
00111              ZCF     = ZF*(XCFN-XXCFN)
00112              ZM      = EXTSMP+EXTIMP
00113              ZMM     = ZM*(1-XCMP)
00114              ZCM     = ZM*(XCMP-XXCMP)
00114         C
00114         C    FIN
00114         C
00115              DO 10 I=1,5
00120              TM       = TO*TPR(I)
00121              EMITMP(I)     = EMIT(TM)
00122              DO 10 J=1,5
00125              TFINN   = TO*TFIN(J,I)
00126           10 EMITFN(J,I)  = EMIT(TFINN)
00131              DO  60 K=1,5
00134              DO 30 IL=1,5
00137              DO 20 JL=1,5
00142              X        = CSF*SS(JL,IL,K)*EBFN(IL,JL)
00143              AUX1(JL) = X*(XXMP(IL,JL)-XXXMP(IL,JL))
00144           20 AUX3(JL) = X*(EMITFN(IL,JL)-XXMP(IL,JL))
00146              AUX2(IL) = DEFNT (AUX1,DXX2,5)+AUX1(1)*DXX2/2.0
00147           30 AUX4(IL) = DEFNT (AUX3,DXX2,5)+AUX3(1)*DXX2/2.0
00151              DO 35 IL=1,5
00154              Y          = SSTT(IL,K)*EBMP(IL)
00155              AUX1(IL) = Y*(XXFN(IL)-XXXFN(IL))
00156           35 AUX3(IL) = Y*(EMITMP(IL)-XXFN(IL))
00160              DO  60 I=1,5
00163              DO  60 J=1,5
00166              ALPHFN(I,J,K) = (XXFN(K)*EBMP(K)+DEFNT(AUX1,0.25,5)+DEFNT(AUX2,
00166             1                0.25,5)+ZCM)/(EMITMP(K)*EBMP(K)+DEFNT(AUX3,0.25,
00166             2                5)+DEFNT(AUX4,0.25,5)+ZMM)
00166         C
00166         C
00167           60 ALPHFN(I,J,6) = XCFN
00167         C
00167         C    CHANNEL
00167         C
00173              DO 120 K=1,5
00176              DO 90  I=1,5
00201              DO 90  J=1,5
00204              L          = J+5*(I-1)
00205              DO 80 JL=1,5
00210              X          = SS(I,J,JL)*EBMP(JL)
00211              AUX1(JL) = X*(XXFN(JL)-XXXFN(JL))
00212           80 AUX3(JL) = X*(EMITMP(JL)-XXFN(JL))
00212         C
00214           90 ALPHMP(K,L)  = (XXMP(J,I)*EBFN(J,I)+DEFNT(AUX1,0.25,5)+ZCF)/
00214             1             (EMITFN(J,I)*EBFN(J,I)+DEFNT(AUX3,0.25,5)+ZFM)
00214         C
00217              DO 95  I=1,5
00222              DO 93 IL=1,5
00225              DO 92 JL=1,5
00230              X        = CSF*SS(JL,IL,K)*EBFN(IL,JL)
00231              AUX1(JL) = X*(XXMP(IL,JL)-XXXMP(IL,JL))
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          92 AUX3(JL) = X*(EMITFN(IL,JL)-XXMP(IL,JL))
             AUX2(IL) = DEFNT (AUX1,DXX2,5)+AUX1(1)*DXX2/2.0
          93 AUX4(IL) = DEFNT (AUX3,DXX2,5)+AUX3(1)*DXX2/2.0
             DO 94 IL=1,5
             Y        = SSTT(IL,I)*EBMP(IL)
             AUX1(IL) = Y*(XXFN(IL)-XXXFN(IL))
          94 AUX3(IL) = Y*(EMITMP(IL)-XXFN(IL))
          95 ALPHMP(K,25+I)= (XXFN(I)*EBMP(I)+DEFNT(AUX1,0.25,5)+DEFNT(AUX2,
            1                0.25,5)+ZCM)/(EMITMP(I)*EBMP(I)+DEFNT(AUX3,0.25,
            2                5)+DEFNT(AUX4,0.25,5)+ZMM)
      C
         120 ALPHMP(K,31) = XCMP
             RETURN
             END
```

END OF COMPILATION: NO DIAGNOSTICS.

@HDG,P ****** ADIABH ******

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****** ADIABH ******                                                      DATE 071372      PAGE     1

@FOR,S ME*NASA5.ADIABH,ME*NASA5.ADIABH
FOR S9A-07/13/72-20:52:57 (0,)

   SUBROUTINE ADIABH    ENTRY POINT 000506

   STORAGE USED: CODE(1) 000522; DATA(0) 000451; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003    ADBH    000352

   EXTERNAL REFERENCES (BLOCK, NAME)

    0004    NUSA
    0005    RHOF
    0006    VISC
    0007    CPF
    0010    THCF
    0011    THCFN
    0012    EMIT
    0013    TTIPS
    0014    PDERIV
    0015    FMINV
    0016    NPRT$
    0017    NI02$
    0020    NSTOP$
    0021    EXP
    0022    NWDU$
    0023    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000     000174 1005F     0001     000004 113G      0001     000074 131G      0000     000373 15F       0001     000124 150G
    0001     000161 157G      0001     000167 165G      0001     000201 173G      0001     000271 205G      0001     000326 231G
    0001     000401 255G      0001     000420 263G      0001     000445 276G      0000     000316 5F        0001     000077 55L
    0001     000115 60L       0001     000322 76L       0001     000346 81L       0001     000336 815L      0001     000356 82L
    0001     000362 86L       0001     000433 89L       0001     000441 895L      0000 R 000000 A         0003 R 000001 AL
    0003 R 000161 CONFL     0003 R 000173 CONFNA    0003 R 000147 CP        0007 R 000000 CPF       0003 R 000000 D
    0000 R 000144 DHAB      0003 R 000326 DTL       0003 R 000244 EFF       0003 R 000205 EMIS      0012 R 000000 EMIT
    0003 R 000013 H         0003 R 000231 HAB       0000 R 000170 HABR      0000 I 000156 I         0000 I 000163 ICNT
    0000     000425 INJP$     0000 I 000164 IT        0000 I 000173 J         0000 I 000171 J1        0000 I 000172 J2
    0003 R 000064 M         0000 I 000160 NSTOP     0003 I 000076 NT        0000 I 000162 NTM1      0000 I 000161 NT1
    0004 I 000000 NUSA      0014 R 000000 PDERIV    0003 R 000052 PIN       0003 R 000314 QOUT      0000 R 000157 RHO
    0005 R 000000 RHOF      0003 R 000217 TB        0000 R 000167 TF        0003     000026 TH        0010 R 000000 THCF
    0011 R 000000 THCFN     0003 R 000040 TIN       0003 R 000270 TL        0000 R 000165 TL1       0000 R 000166 TL2
    0003 R 000340 TOUT      0003     000077 TSTAR     0006 R 000000 VISC      0003 R 000135 VSC


00101       1*            SUBROUTINE ADIABH(ITST)
00103       2*                PARAMETER NTP = 10
00104       3*                PARAMETER NTP1 = NTP+1
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00105                PARAMETER NTPSQ = NTP*NTP
00106                REAL M
00107                COMMON /ADBH/ D,AL(NTP),H(NTP1),TH(NTP),TIN(NTP),PIN(NTP),
00107         1      M(NTP),NT,TSTAR(NTP,3),VSC(NTP),CP(NTP),CONFL(NTP),
00107         2      CONFNA(NTP),EMIS(NTP),TB(NTP),HAB(NTP1),EFF(NTP,2),TL(NTP,2),
00107         3      QOUT(NTP),DTL(NTP),TOUT(NTP)
00110          DIMENSION A(NTPSQ),DHAB(NTP)
00111          DEFINE U(I) = 3.1415927*CONFL(I)*AL(I)*NUSA(48.0*M(I)/(3.1415927*
00111         1D*VSC(I)),VSC(I)*CP(I)/CONFL(I),D/(12*AL(I)))/(M(I)*CP(I))
00112                DO 10 I = 1,NT
00115                RHO = RHOF(PIN(I),TIN(I))
00116                VSC(I) = VISC(RHO,TIN(I))
00117                CP(I) = CPF(RHO,TIN(I))
00120                CONFL(I) = THCF(RHO,TIN(I))
00121                CONFNA(I) = THCFN(TIN(I))
00122    10          EMIS(I) = EMIT(TIN(I))
00124          NSTOP=20
00125          NT1=NT+1
00126          NTM1=NT-1
00127          ICNT=1
00130          DO 2 IT=1,NT1
00133    2     HAB(IT)=H(IT)
00135    55    CONTINUE
00136          ICNT=ICNT+1
00137          IF(ICNT.LE.NSTOP)GO TO 60
00141          PRINT 1005,NSTOP
00144    1005  FORMAT('0PROGRAM STOPPED IN SUBROUTINE ADIABH BECAUSE THE DISTANCE
00144         > TO AN',/,' ADIABATIC PLANE FAILED TO CONVERGE WITHIN THE ALLOWABL
00144         >E RANGE OF
00144         >',/,' VALUES(2.5% AND 97.5% OF TOTAL FIN WIDTH) AFTER',I3,' ITERAT
00144         >IONS.',/,' THIS IS PROBABLY BECAUSE THE INPUT CONDITIONS DO NOT AL
00144         >LOW A SOLUTION',/,' IN THIS RANGE. HOWEVER THE NUMBER OF ITERATION
00144         >S CAN BE INCREASED ',/,' BY ASSIGNING A LARGER VALUE TO NSTOP IN S
00144         >UBROUTINE ADIABH.')
00145                STOP
00146    60    CONTINUE
00147          DO 6 IT=1,NT
00152                CALL TTIPS(IT,ITST,HAB(IT),H(IT+1)*2.0-HAB(IT+1),TL1,TL2)
00153                TL(IT,1) = TL1
00154    6           TL(IT,2) = TL2
00156          DO 7 IT=1,NTM1
00161          DTL(IT)=TL(IT,2)-TL(IT+1,1)
00162    7     CONTINUE
00164          DO 75 IT=1,NTM1
00167    75    IF(ABS(DTL(IT)).GT.0.05)GO TO 76
00172                DO 752 IT = 1,NT
00175                TF = (TIN(IT)-TB(IT))*(1.0-EXP(-U(IT)))
00176                QOUT(IT) = M(IT)*CP(IT)*TF
00177    752         TOUT(IT) = TIN(IT)-TF
00201                WRITE(6,5)
00203    5           FORMAT(////,7X,'BULK TEMP',5X,'INCHES TO ADIABATIC PLANE',
00203         1      5X,'PER CENT FIN EFFICIENCY',5X,'FIN TIP TEMP  DEG R',
00203         2      5X,'OUTLET TEMP',5X,'HEAT REJECTED',/,1X,'TUBE',4X,
00203         3      'DEG R',11X,'LEFT',8X,'RIGHT',12X,2('LEFT',8X,'RIGHT',9X),
00203         4      'DEG R',11X,'BTU/HR',/)
00204                DO 100 I = 1,NT
00207                HABR = H(I+1)*2.0-HAB(I+1)
```

```
00210      100      WRITE(6,15) I,TB(I),HAB(I),HABR,EFF(I,1),EFF(I,2),TL(I,1),
00210           1   TL(I,2),TOUT(I),QOUT(I)
00225       15      FORMAT(1X,I2,3X,1PE10.4,6X,1PE10.4,2X,1PE10.4,7X,
00225           1   2(1PE10.4,2X,1PE10.4,4X),1PE10.4,7X,1PE10.4)
00226            RETURN
00227       76   CONTINUE
00230            DO 88 IT=1,NTM1
00233            IF(NT.NE.2)GO TO 815
00235            J1=0
00236            J2=0
00237            GO TO 86
00240      815   IF(IT.NE.1)GO TO 81
00242            J1=0
00243            J2=1
00244            GO TO 86
00245       81    IF(IT.NE.NTM1)GO TO 82
00247            J1=-1
00250            J2=0
00251            GO TO 86
00252       82   J1=-1
00253            J2=1
00254       86    DO 88 J=J1,J2
00257       88   A(IT*NTM1-1*NTM1+J*NTM1+IT)=PDERIV(J,IT,ITST)
00262            DO 8 IT=1,NTM1
00265        8   DHAB(IT)=-DTL(IT)
00267            IF(NT.NE.2)GO TO 89
00271            DHAB(1)=-DTL(1)/A(1)
00272            GO TO 895
00273       89   CALL FMINV(A,DHAB,NTM1,NT)
00274      895   CONTINUE
00275            DO 9 IT=2,NT
00300            HAB(IT)=HAB(IT)+DHAB(IT-1)
00301            HAB(IT)=MIN(HAB(IT),1.95*H(IT))
00302            HAB(IT)=MAX(.05*H(IT),HAB(IT))
00303        9   CONTINUE
00305            GO TO 55
00306            END

      END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  ALTVEL  ******
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```
@FOR,S ME*NASA5.ALTVEL,ME*NASA5.ALTVEL
FOR S9A-07/13/72-20:53:00 (0,)

   FUNCTION ALTVEL      ENTRY POINT 000151

   STORAGE USED: CODE(1) 000207; DATA(0) 000016; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   YINT
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000052 1L       0001   000120 2L       0001   000124 3L       0001   000133 4L       0000 R 000000 ALTVEL
    0000   000002 INJP$    0000 I 000001 M        0003 R 000000 YINT


00101           FUNCTION ALTVEL (TIME,IOPTN,AVA,AVR,TA,TR,NA,NR)
00101        C
00101        C   THIS SUBROUTINE COMPUTES :
00101        C       ALTITUDE AND VELOCITY OF ORBITER AS A FUNCTION OF TIME FROM
00101        C       LAUNCH  (IOPTN = 0 ) OR TIME FROM PASSING THROUGH 400,000 FEET
00101        C       FOR REENTRY ( IOPTN = 0 )
00101        C                                   TIME IN SECS, ALTITUDE IN FEET
00101        C                                   AND VELOCITY IN FEET/SEC
00101        C
00103           DIMENSION TA(NA),TR(NR),AVA(NA),AVR(NR)
00104           IF (TIME .GT. TA(NA) .AND. IOPTN .EQ. 0)  GO TO 3
00106           IF (TIME .GT. TR(NR) .AND. IOPTN .EQ. 1)  GO TO 4
00110           M      =  2
00111         1 IF (IOPTN .EQ. 0) ALTVEL =  YINT(TA,AVA,NA,M,TIME)
00113           IF (IOPTN .EQ. 1) ALTVEL =  YINT(TR,AVR,NR,M,TIME)
00115           IF (ALTVEL .LT. 0.0 .AND. M .GT. 2) GO TO 2
00117           RETURN
00120         2 M      =  M-1
00121           GO TO 1
00122         3 ALTVEL  =  AVA(NA)
00123           RETURN
00124         4 ALTVEL  =  AVR(NR)
00125           RETURN
00126           END

     END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  ATMOS  ******
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```
@FOR,S ME*NASA5.ATMOS,ME*NASA5.ATMOS
FOR S9A-07/13/72-20:53:03 (0,)

     SUBROUTINE ATMOS      ENTRY POINT 000237

     STORAGE USED: CODE(1) 000261; DATA(0) 000211; BLANK COMMON(2) 000000

     EXTERNAL REFERENCES (BLOCK, NAME)

      0003    POLY
      0004    CPAIR
      0005    NWDU$
      0006    NI02$
      0007    SQRT
      0010    NERR3$

     STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

      0001    000105 10L      0001    000137 15L      0001    000070 2L       0001    000161 20L      0001    000057 231G
      0001    000012 30L      0000    000116 35F      0001    000022 40L      0000    000136 45F      0001    000032 60L
      0000 R 000041 A         0000 R 000055 B         0000 R 000074 CF1       0004 R 000000 CPAIR     0000 R 000107 CPATM
      0000 R 000104 DH        0000 R 000100 ELEVM     0000 R 000110 GAMATM    0000 R 000102 GEOH      0000 R 000101 GEOHM
      0000 R 000007 GH        0000 R 000031 GT        0000 R 000000 H         0000 I 000103 I         0000   000201 INJP$
      0000 I 000105 J         0000 R 000077 MWT       0000 R 000113 PATM      0003 R 000000 POLY      0000 R 000075 PSL
      0000 R 000112 PZ        0000 R 000115 RHOATM    0000 R 000076 RSL       0000 R 000072 RU        0000 R 000073 RU1
      0000 R 000114 RZ        0000 R 000020 T         0000 R 000106 TMK       0000 R 000071 WMO       0000 R 000111 Z


 00101      1*          SUBROUTINE ATMOS (ELEV,TATM,CATM)
 00101      2*    C
 00101      3*    C  THIS SUBROUTINE COMPUTES :
 00101      4*    C       PROPERTIES FOR ATMOSPHERIC AIR UP TO 528,000 FEET (100 MILES OR 161 KM)
 00101      5*    C       PROPERTIES FOR AN ALTITUDE LESS THAN 301,000 FEET TAKEN FROM
 00101      6*    C       U. S. STANDARD ATMOSPHERE FOR  1966. PROPERTIES FOR ALTITUDES BETWEEN
 00101      7*    C       301,000 FEET AND 528,000 FEET ARE TAKEN FROM APPROXIMATE ANALYSIS GIVEN
 00101      8*    C       IN THE SAME REFERENCE. ERRORS IN PRESSURE AND DENSITY ARE NO LARGER
 00101      9*    C       THAN 5 PERCENT FOR ALTITUDES GREATER THAN 301,000 FEET AND LESS
 00101     10*    C       THAN 528,000 FEET.
 00101     11*    C                                            ELEVATION IN FEET
 00101     12*    C                                            TEMPERATURE IN DEG R.
 00101     13*    C                                            SPECIFIC HEAT IN BTU/LBM R
 00101     14*    C                                            VEL OF SOUND IN FT/SEC
 00101     15*    C
 00103     16*          DIMENSION H(7),GH(9),T(9),GT(8),A(12),B(12)
 00104     17*          DATA H(1),H(2),H(3),H(4),H(5),H(6),H(7) /0.0,1.0,-1.5731262E-07,2.
 00104     18*         14656553E-14,-3.8667054E-21,6.0621354E-28,-9.5013649E-35/,GH(1),GH(
 00104     19*         22),GH(3),GH(4),GH(5),GH(6),GH(7),GH(8),GH(9) /0.0,11.0,20.0,32.0,4
 00104     20*         37.0,52.0,61.0,79.0,90.0/,T(1),T(2),T(3),T(4),T(5),T(6),T(7),T(8),T
 00104     21*         4(9) /288.15,216.65,216.65,228.65,270.65,270.65,252.65,180.65,180.6
 00104     22*         55/,GT(1),GT(2),GT(3),GT(4),GT(5),GT(6),GT(7),GT(8) /-6.5,0.0,1.0,2
 00104     23*         6.8,0.0,-2.0,-4.0,0.0/,WMO,RU,RU1/ 28.9644,8314.32,1545.31/
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```
00104           7 CF1/ 1000.0/,PSL,RSL /2116.22657,0.07647438/
00154            DATA A(1),A(2),A(3),A(4),A(5),A(6),A(7),A(8),A(9),A(10),A(11),
00154           1A(12)/
00154           1      0.10E+01,  0.3533367370E-01,  -0.7474788290E-03,
00154           2      0.2121572232E-03,  -0.1325255219E-04,  0.5344159692E-06,
00154           3      -0.1322745646E-07,  0.1965359762E-09,  -0.1723714966E-11,
00154           4      0.8707590786E-14,  -0.2341816445E-16,  0.2597772972E-19/,
00154           5B(1),B(2),B(3),B(4),B(5),B(6),B(7),B(8),B(9),B(10),B(11),B(12)/
00154           6      0.10E+01,  0.3393495800E-01,  -0.3433553057E-02,
00154           7      0.5497466428E-03,  -0.3228358326E-04,  0.1106617734E-05,
00154           8      -0.2291755793E-07,  0.2902146443E-09,  -0.2230070938E-11,
00154           9      0.1010575266E-13,  -0.2482089627E-16,  0.2548769715E-19/
00205            REAL MWT
00206            IF (ELEV .LT. 0.0) GO TO 30
00210            IF (ELEV .GT. 528000.) GO TO 40
00212            GO TO 60
00213        30 WRITE (6,35)
00215        35 FORMAT (1X,'AN ATTEMPT HAS BEEN MADE TO EVALUATE ATMOSPHERIC PROPE
00215          1RTIES FOR NEGITIVE ALTITUDES')
00216            RETURN
00217        40 WRITE (6,45)
00221        45 FORMAT (1X,'AN ATTEMPT HAS BEEN MADE TO EVALUATE ATMOSPHERIC PROPE
00221          1RTIES FOR AN ALTITUDE EXCEEDING 100 MILES')
00222            RETURN
00223        60 IF (ELEV .GT. 301000.)  GO TO 20
00225            ELEVM  = ELEV*0.3048
00226            GEOHM  = POLY(7,H,ELEVM)
00227            GEOH   = GEOHM/0.3048
00230            DO 1  I=1,9
00233            DH     = GH(I)-GEOHM/CF1
00234            IF (DH.GT.0.0) GO TO 2
00236         1 CONTINUE
00240         2 J      = I-1
00241            DH     = GH(J)-GEOHM/CF1
00242            TMK    = T(J)-GT(J)*DH
00243            TATM   = TMK*1.8
00244        10 CPATM   =  CPAIR(TATM)
00245            IF (ELEV .GT. 301000.) GO TO 15
00247            GAMATM =  CPATM/(CPATM-0.0686)
00250            CATM   = SQRT(1.4*RU*TMK/WMO)/0.3048
00251            RETURN
00252        15 GAMATM =  CPATM/(CPATM-(1.98585/MWT))
00253            CATM   =  SQRT(GAMATM*RU*TMK/MWT)/0.3048
00254            RETURN
00255        20 Z      =  ELEV/(3280.8399)
00256            MWT    =  28.9644-0.0309491*(Z-90.0)
00257            PZ     = POLY(12,A,Z)
00260            PATM   = PSL/(PZ**4)
00261            RZ     = POLY(12,B,Z)
00262            RHOATM = RSL/(RZ**4)
00263            TATM   =  PATM*MWT/(RHOATM*1545.31)
00264            TMK    = TATM/1.8
00265            GO TO 10
00266            END

      END OF COMPILATION:        NO  DIAGNOSTICS.
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```
@FOR,S ME*NASA5.AVGEMT/SCZ93,ME*NASA5.AVGEMT/SCZ93
FOR S9A-07/13/72-20:53:05 (0,)

   SUBROUTINE AVGEMT    ENTRY POINT 000110

   STORAGE USED: CODE(1) 000121; DATA(0) 000040; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003   AVGABS 000251

   EXTERNAL REFERENCES (BLOCK, NAME)

    0004   POLY
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001    000004 124G      0001    000024 132G      0000 R 000000 A         0000 R 000005 B         0000 I 000016 I
    0000    000025 INJP$     0000 I 000014 J         0004 R 000000 POLY      0000 R 000013 TALB      0003 R 000100 TFIN
    0000 R 000017 TFNX       0000 R 000015 TMPX      0003 R 000244 TPR       0000 R 000012 TSOL      0003 R 000062 XXFN
    0003 R 000000 XXMP       0003 R 000071 XXXFN     0003 R 000031 XXXMP


00101            SUBROUTINE AVGEMT(TO)
00101       C
00101       C   THIS SUBROUTINE COMPUTES :
00101       C     THE NECESSARY VARIABLES FOR THE COMPUTATIONS OF THE AVERAGE
00101       C     SURFACE COATING EMITTANCE
00101       C
00103            COMMON/AVGABS/XXMP(5,5),XXXMP(5,5),XXFN(7),XXXFN(7),
00103           1              TFIN(10,10),TPR(5)
00104            DIMENSION A(5), B(5)
00105            DATA  A(1),A(2),A(3),A(4),A(5)/0.7804112E+00, -0.5527205E-04,
00105           1      0.2530228E-06, -0.3229181E-09, 0.8854202E-13/
00105           2      B(1),B(2),B(3),B(4),B(5)/0.6538383E+00, 0.1144374E-03,
00105           3      -0.2432286E-07, -0.1437500E-09, 0.4947915E-13/
00120            DATA TSOL,TALB/10400.0,480.0/
00123            DO  1  J = 1,5
00126            TMPX     = TPR(J)*TO
00127            XXFN(J)  = POLY(5,A,TMPX)
00130            XXXFN(J) = POLY(5,B,TMPX)
00131            DO  1  I = 1,5
00134            TFNX     = TFIN(J,I)*TO
00135            XXMP(J,I)= POLY(5,A,TFNX)
00136          1 XXXMP(J,I)= POLY(5,B,TFNX)
00141            XXFN(6)  = POLY(5,A,TALB)
00142            XXXFN(6) = POLY(5,B,TALB)
00143            XXFN(7)  = 0.07156
00144            XXXFN(7) = 0.030562
00145            RETURN
```

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****** AVGEMT/SCZ93 ******                                                          DATE 071372        PAGE      2

00146     28*           END
      END OF COMPILATION:         NO  DIAGNOSTICS.

@HDG,P  ******  BETA/CFFC43  ******
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******  BETA/CFFC43  ******                                                                    DATE 071372        PAGE      1

@FOR,S ME*NASA5.BETA/CFFC43,ME*NASA5.BETA/CFFC43
FOR S9A-07/13/72-20:53:07 (0,)

   FUNCTION BETA          ENTRY POINT 000015

   STORAGE USED: CODE(1) 000017; DATA(0) 000010; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000000 BETA      0000    000003 INJP$     0000 R 000001 X1        0000 R 000002 X2


00101          FUNCTION BETA(RHO,T)
00101     C
00101     C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101     C       COEFFICIENT OF THERMAL EXPANSION AS A FUNCTION OF DENSITY
00101     C       (SLUG/QU.FT) AND TEMPERATURE (R) OF FC-43
00101     C                                         UNITS 1/R
00101     C
00103          DATA X1,X2 /157.0883,-0.076167/
00106          BETA = -X2/(X1+X2*T)
00107          RETURN
00110          END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  BETA/CFFC75  ******
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****** BETA/CFFC75 ******                                                    DATE 071372        PAGE      1

@FOR,S ME*NASA5.BETA/CFFC75,ME*NASA5.BETA/CFFC75
FOR S9A-07/13/72-20:53:09 (0,)

   FUNCTION BETA        ENTRY POINT 000015

   STORAGE USED: CODE(1) 000017; DATA(0) 000010; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000000 BETA       0000   000003 INJP$     0000 R 000001 X1        0000 R 000002 X2


00101      1*          FUNCTION BETA(RHO,T)
00101      2*     C
00101      3*     C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*     C       COEFFICIENT OF THERMAL EXPANSION AS A FUNCTION OF DENSITY
00101      5*     C       (SLUG/QU.FT) AND TEMPERATURE (R) OF FC-75
00101      6*     C                                        UNITS 1/R
00101      7*     C
00103      8*          DATA X1,X2 /155.522,-0.085/
00106      9*          BETA = -X2/(X1+X2*T)
00107     10*          RETURN
00110     11*          END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  BETA/CFHE  ******
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****** BETA/CFHE ******                                                          DATE 071372        PAGE      1

@FOR,S ME*NASA5.BETA/CFHE,ME*NASA5.BETA/CFHE
FOR S9A-07/13/72-20:53:10 (0,)

   FUNCTION BETA        ENTRY POINT 000106

   STORAGE USED: CODE(1) 000112; DATA(0) 000037; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000005 A         0000 R 000014 ALPHA     0000 R 000002 A1        0000 R 000000 BETA      0000 R 000003 B1
    0000 R 000004 C         0000 R 000017 DPDRHO    0000 R 000015 DPDT      0000 R 000016 DPDV      0000   000026 INJP$
    0000 R 000001 R         0000 R 000006 RHOX      0000 R 000013 TM2       0000 R 000007 TX        0000 R 000010 V
    0000 R 000011 VM2       0000 R 000012 VM3


00101            FUNCTION BETA(RHO,T)
00101      C
00101      C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101      C        COEFFICIENT OF THERMAL EXPANSION AS A FUNCTION OF DENSITY
00101      C        (SLUG/CU.FT) AND TEMPERATURE (R) OF HELIUM
00101      C                                          UNITS 1/R
00101      C
00103            DATA R,A1,B1,C,A /2077.02,136.9595,3.5002295E-03,10.000658,1.49610
00103           13E-02/
00111            RHOX  = RHO*515.4275
00112            TX    = T/1.8
00113            V     = 1.0/RHOX
00114            VM2   = RHOX*RHOX
00115            VM3   = RHOX*VM2
00116            TM2   = 1.0/(TX*TX)
00117            ALPHA = C*RHOX/(TX**3)
00120            DPDT  = R*(V+B1)*VM2*(1.0+2.0*ALPHA)
00121            DPDV  =-R*TX*VM2*(1.0+2.0*RHOX*B1)+A1*VM3*(2.0-3.0*A*RHOX)+R*C*VM3
00121           1*TM2*(2.0+3.0*B1*RHOX)
00122            DPDRHO=-DPDV/VM2
00123            BETA  = DPDT/(DPDRHO*RHOX*1.8)
00124            RETURN
00125            END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  BETA/CFNAK  ******
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****** BETA/CFNAK ******                                              DATE 071372      PAGE    1

@FOR,S ME*NASA5.BETA/CFNAK,ME*NASA5.BETA/CFNAK
FOR S9A-07/13/72-20:53:13 (0,)

   FUNCTION BETA        ENTRY POINT 000015

   STORAGE USED: CODE(1) 000017; DATA(0) 000010; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000000 BETA      0000    000003 INJP$     0000 R 000001 X1        0000 R 000002 X2


 00101       1*              FUNCTION BETA(RHO,T)
 00101       2*        C
 00101       3*        C        THIS FUNCTION SUBPROGRAM COMPUTES :
 00101       4*        C        COEFFICIENT OF THERMAL EXPANSION AS A FUNCTION OF DENSITY
 00101       5*        C        (SLUG/QU.FT) AND TEMPERATURE (R) OF NAK 78.6
 00101       6*        C                                      UNITS 1/R
 00101       7*        C
 00103       8*              DATA X1,X2 /58.773064,-0.008433/
 00106       9*              BETA = -X2/(X1+X2*T)
 00107      10*              RETURN
 00110      11*              END
        END OF COMPILATION:       NO  DIAGNOSTICS.


 @HDG,P  ******  BETA/CFSIL  ******
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@FOR,S ME*NASA5.BETA/CFSIL,ME*NASA5.BETA/CFSIL
FOR S9A-07/13/72-20:53:15 (0,)

   FUNCTION BETA        ENTRY POINT 000162

   STORAGE USED: CODE(1) 000177; DATA(0) 000076; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003    PF
    0004    NWDU$
    0005    NI02$
    0006    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000     000030 1F        0000 R 000001 A1        0000 R 000022 A11       0000 R 000002 A2        0000 R 000003 A3
    0000 R 000004 A4        0000 R 000005 A5        0000 R 000000 BETA      0000 R 000006 B1        0000 R 000023 B11
    0000 R 000007 B2        0000 R 000010 B3        0000 R 000011 B4        0000 R 000012 B5        0000 R 000024 C
    0000 R 000013 C1        0000 R 000025 C11       0000 R 000014 C2        0000 R 000017 DT        0000     000067 INJP$
    0000 R 000026 P         0003 R 000000 PF        0000 R 000027 P1        0000 R 000020 THETA     0000 R 000021 THETA1
    0000 R 000015 T0        0000 R 000016 T01


00101             FUNCTION BETA(RHO,T)
00101       C
00101       C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101       C        COEFFICIENT OF THERMAL EXPANSION AS A FUNCTION OF DENSITY
00101       C             (SLUG/CU.FT) AND TEMPERATURE (R) OF DOW CORNING 200
00101       C             SILICON OIL (1 CS)
00101       C                                     UNITS 1/R
00101       C             TEMPERATURE .GE. 359.67 AND .LE. 859.67
00101       C
00103             DATA A1,A2,A3,A4,A5 /12.35,2.98333,1.1,-0.48333,0.1/,B1,B2,B3,B4,B
00103            15 /-1.5,-0.01333,-1.18,0.57333,-0.1/,C1,C2 /0.7767,-0.0288/,T0,T01
00103            2,DT /559.67,609.67,50.0/
00123             THETA  = (T-T0)/DT
00124             THETA1 = (T-T01)/DT
00125             A11 = (((4.0*A5*THETA+3.0*A4)*THETA+2.0*A3)*THETA+A2)*(1.0E-06)/DT
00126             B11 = (((4.0*B5*THETA+3.0*B4)*THETA+2.0*B3)*THETA+B2)*(1.0E-09)/DT
00127             C   = C1+C2*THETA1
00130             C11 = C2/DT
00131             P   = PF(RHO,T)
00132             P1 = P/144.0-14.696
00133             BETA= -C11/C-A11*P1-B11*P1*P1/2.0
00134             IF (T.LT.360.67.OR.T.GT.860.67.OR.P.GT.146116.224.OR.P.GT.110116.2
00134            124.AND.T.LT.460.67) WRITE(6,1) T,P
00141           1 FORMAT (1H0,67HCOEFFICIENT OF THERMAL EXPANSION OF SILICON OIL, OU
00141            1T OF RANGE, T = ,F10.5,6H, P = ,F15.5,/)
00142             RETURN
00143             END
```

END OF COMPILATION: NO DIAGNOSTICS.

@HDG,P ****** CAPPA/CFFC43 ******

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****** CAPPA/CFFC43 ******                                                    DATE 071372        PAGE     1

@FOR,S ME*NASA5.CAPPA/CFFC43,ME*NASA5.CAPPA/CFFC43
FOR S9A-07/13/72-20:53:17 (0,)

   FUNCTION CAPPA        ENTRY POINT 000010

   STORAGE USED: CODE(1) 000012; DATA(0) 000006; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000000 CAPPA      0000   000001 INJP$



00101              FUNCTION CAPPA(RHO,T)
00101        C
00101        C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101        C        ISOTHERMAL COMPRESSIBILITY AS A FUNCTION OF DENSITY
00101        C             (SLUG/CU.FT) AND TEMPERATURE (R) OF FC-43
00101        C                                        UNITS SQ.FT/LBF
00101        C
00103              CAPPA = 0.0
00104              RETURN
00105              END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ****** CAPPA/CFFC75 ******
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****** CAPPA/CFFC75 ******                                                        DATE 071372        PAGE      1

@FOR,S ME*NASA5.CAPPA/CFFC75,ME*NASA5.CAPPA/CFFC75
FOR S9A-07/13/72-20:53:19 (0,)

   FUNCTION CAPPA        ENTRY POINT 000010

   STORAGE USED: CODE(1) 000012; DATA(0) 000006; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000000 CAPPA      0000    000001 INJP$


00101        1*              FUNCTION CAPPA(RHO,T)
00101        2*      C
00101        3*      C          THIS FUNCTION SUBPROGRAM COMPUTES :
00101        4*      C          ISOTHERMAL COMPRESSIBILITY AS A FUNCTION OF DENSITY
00101        5*      C               (SLUG/CU.FT) AND TEMPERATURE (R) OF FC-75
00101        6*      C                                         UNITS SQ.FT/LBF
00101        7*      C
00103        8*              CAPPA = 0.0
00104        9*              RETURN
00105       10*              END

        END OF COMPILATION:        NO  DIAGNOSTICS.

@HDG,P  ******  CAPPA/CFHE  ******
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****** CAPPA/CFHE ******                                                    DATE 071372        PAGE    1

QFOR,S ME*NASA5.CAPPA/CFHE,ME*NASA5.CAPPA/CFHE
FOR S9A-07/13/72-20:53:21 (0,)

   FUNCTION CAPPA       ENTRY POINT 000064

   STORAGE USED: CODE(1) 000067; DATA(0) 000031; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000005 A        0000 R 000002 A1       0000 R 000003 B1       0000 R 000004 C        0000 R 000000 CAPPA
    0000 R 000013 DPDV     0000   000022 INJP$    0000 R 000001 R        0000 R 000006 RHOX     0000 R 000012 TM2
    0000 R 000007 TX       0000 R 000010 VM2      0000 R 000011 VM3


00101       1*           FUNCTION CAPPA(RHO,T)
00101       2*     C
00101       3*     C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101       4*     C        ISOTHERMAL COMPRESSIBILITY AS A FUNCTION OF DENSITY
00101       5*     C             (SLUG/CU.FT) AND TEMPERATURE (R) OF HELIUM
00101       6*     C                                      UNITS SQ.FT/LBF
00101       7*     C
00103       8*           DATA R,A1,B1,C,A /2077.02,136.9595,3.5002295E-03,10.000658,1.49610
00103       9*          13E-02/
00111      10*           RHOX  = RHO*515.4275
00112      11*           TX    = T/1.8
00113      12*           VM2   = RHOX*RHOX
00114      13*           VM3   = RHOX*VM2
00115      14*           TM2   = 1.0/(TX*TX)
00116      15*           DPDV  =-R*TX*VM2*(1.0+2.0*RHOX*B1)+A1*VM3*(2.0-3.0*A*RHOX)+R*C*VM3
00116      16*          1*TM2*(2.0+3.0*B1*RHOX)
00117      17*           CAPPA =-47.872*RHOX/DPDV
00120      18*           RETURN
00121      19*           END

       END OF COMPILATION:        NO  DIAGNOSTICS.

QHDG,P  ****** CAPPA/CFNAK  ******
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****** CAPPA/CFNAK ******                                                        DATE 071372        PAGE      1

@FOR,S ME*NASA5.CAPPA/CFNAK,ME*NASA5.CAPPA/CFNAK
FOR S9A-07/13/72-20:53:25 (0,)

   FUNCTION CAPPA       ENTRY POINT 000052

   STORAGE USED: CODE(1) 000055; DATA(0) 000032; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000017 BETA      0000 R 000000 CAPPA     0000 R 000015 CP        0000 R 000010 C1        0000 R 000011 C2
    0000 R 000007 DT        0000   000023 INJP$     0000 R 000016 RHOF      0000 R 000014 THETA     0000 R 000006 T0
    0000 R 000020 VELS      0000 R 000012 V1        0000 R 000013 V2        0000 R 000001 X1        0000 R 000002 X2
    0000 R 000003 X3        0000 R 000004 X4        0000 R 000005 X5


00101      1*           FUNCTION CAPPA(RHO,T)
00101      2*     C
00101      3*     C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*     C        ISOTHERMAL COMPRESSIBILITY AS A FUNCTION OF DENSITY
00101      5*     C              (SLUG/CU.FT) AND TEMPERATURE (R) OF NAK 78.6
00101      6*     C                                      UNITS SQ.FT/LBF
00101      7*     C
00103      8*           DATA X1,X2,X3,X4,X5 /0.2255,-0.016292,0.005396,-0.000758,0.000054/
00103      9*          1,T0,DT /659.67,300.0/,C1,C2 /58.773064,-0.008433/,V1,V2 /6296.9267
00103     10*          2,0.99/
00117     11*           THETA = (T-T0)/DT
00120     12*           CP    = (((X5*THETA+X4)*THETA+X3)*THETA+X2)*THETA+X1
00121     13*           RHOF  = C1+C2*T
00122     14*           BETA  = -C2/RHOF
00123     15*           VELS  = V1+V2*T
00124     16*           CAPPA = (32.174/(VELS*VELS)+BETA*BETA*T/(CP*778.26))/RHOF
00125     17*           RETURN
00126     18*           END
       END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  CAPPA/CFSIL  ******
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```
@FOR,S ME*NASA5.CAPPA/CFSIL,ME*NASA5.CAPPA/CFSIL
FOR S9A-07/13/72-20:54:12 (0,)

   FUNCTION CAPPA       ENTRY POINT 000132

   STORAGE USED: CODE(1) 000146; DATA(0) 000064; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   PF
    0004   NWDU$
    0005   NI02$
    0006   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000     000023 1F        0000 R 000016 A       0000 R 000001 A1      0000 R 000002 A2      0000 R 000003 A3
    0000 R 000004 A4          0000 R 000005 A5      0000 R 000017 B       0000 R 000006 B1      0000 R 000007 B2
    0000 R 000010 B3          0000 R 000011 B4      0000 R 000012 B5      0000 R 000000 CAPPA   0000 R 000014 DT
    0000     000055 INJP$     0000 R 000020 P       0003 R 000000 PF      0000 R 000021 P1      0000 R 000015 THETA
    0000 R 000022 TK          0000 R 000013 T0


00101      1*          FUNCTION CAPPA(RHO,T)
00101      2*     C
00101      3*     C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*     C       ISOTHERMAL COMPRESSIBILITY AS A FUNCTION OF DENSITY
00101      5*     C            (SLUG/CU.FT) AND TEMPERATURE (R) OF DOW CORNING
00101      6*     C            200 SILICON OIL (1 CS)
00101      7*     C                                        UNITS SQ.FT/LBF
00101      8*     C            TEMPERATURE .GE. 359.67 AND .LE. 859.67
00101      9*     C
00103     10*          DATA A1,A2,A3,A4,A5 /12.35,2.98333,1.1,-0.48333,0.1/,B1,B2,B3,B4,
00103     11*         1B5 /-1.5,-0.01333,-1.18,0.57333,-0.1/,T0,DT /559.67,50.0/
00120     12*          THETA = (T-T0)/DT
00121     13*          A  = ((((A5*THETA+A4)*THETA+A3)*THETA+A2)*THETA+A1)*1.0E-06
00122     14*          B  = ((((B5*THETA+B4)*THETA+B3)*THETA+B2)*THETA+B1)*1.0E-09
00123     15*          P  = PF(RHO,T)
00124     16*          P1 = P/144.0-14.696
00125     17*          TK = A+B*P1
00126     18*          CAPPA = TK/144.0
00127     19*          IF (T.LT.360.67.OR.T.GT.860.67.OR.P.GT.146116.224.OR.P.GT.110116.2
00127     20*         124.AND.T.LT.460.67) WRITE(6,1) T,P
00134     21*        1 FORMAT (1H0,61HISOTHERMAL COMPRESSIBILITY OF SILICON OIL, OUT OF R
00134     22*         1ANGE, T = ,F10.5,6H, P = ,F15.5,/)
00135     23*          RETURN
00136     24*          END

     END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@FOR,S ME*NASA5.CNTLM,ME*NASA5.CNTLM
FOR S9A-07/13/72-20:54:17 (0,)

    SUBROUTINE CNTLM      ENTRY POINT 001771

    STORAGE USED: CODE(1) 002060; DATA(0) 003423; BLANK COMMON(2) 001115

     COMMON BLOCKS:

     0003    SRTCNV 000003
     0004    QRD    003670
     0005    QIN    001610
     0006    GEOM   000020
     0007    FLDINL 000457
     0010    DVCMFL 000002

    EXTERNAL REFERENCES (BLOCK, NAME)

     0011    THCFN
     0012    CPFN
     0013    DEFINT
     0014    YINT
     0015    HFL
     0016    CPTB
     0017    CPMP
     0020    FINT
     0021    SQRT
     0022    NERR2$
     0023    ALOG
     0024    NWDU$
     0025    NI02$
     0026    NI01$
     0027    NERR3$

    STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

     0001    000206 10L       0001    000471 100L      0001    000506 105L      0001    000162 147G      0001    000227 15L
     0001    000253 177G      0001    000110 2L        0001    000244 20L       0001    000347 230G      0001    000311 25L
     0001    000127 3L        0001    000332 30L       0001    000617 321G      0001    000632 330G      0001    000670 343G
     0001    000703 346G      0001    001061 374G      0001    001255 422G      0001    001274 426G      0001    001333 440G
     0001    001403 453G      0001    001437 464G      0001    000166 5L        0001    000340 50L       0001    000517 500L
     0001    000522 505L      0001    000542 506L      0001    000555 507L      0000    002504 509F      0000    002554 510F
     0001    001537 511G      0001    001002 513L      0001    001054 514L      0000    002605 515F      0000    003031 516F
     0001    001553 522G      0000    003057 530F      0001    001562 530G      0000    003064 535F      0001    001664 543L
     0001    001670 544L      0001    000405 55L       0000    003310 550F      0000    003317 555F      0000    003322 560F
     0001    001653 560G      0001    001176 600L      0001    000416 65L       0001    000147 7L        0001    000421 70L
     0000 R  002430 ASTR1     0000 R  002431 ASTR2     0000 R  000310 AUX1      0002 R  000562 AUX2      0000 R  000322 AUX3
     0000 R  000334 AUX4      0000 R  000346 AUX5      0002    000752 COB       0002 R  001107 COH       0000 R  002446 CONDMF
     0000 R  002454 COND1     0000 R  002455 COND2     0002 R  000574 CONFN     0000 R  002456 CONMF1    0002 R  000740 CONMP
     0012 R  000000 CPFN      0000 R  002467 CPFN1     0017 R  000000 CPMP      0000 R  002474 CPMP1     0016 R  000000 CPTB
     0000 R  002472 CPTB1     0002    001070 CP0       0004    003465 CSF       0000 R  002502 DEDOT     0000 R  002501 DEDT
     0013 R  000000 DEFINT    0002    001072 DELTA     0000 R  002464 DENTH     0000 R  002503 DIFE      0002    000764 DOB
     0000 R  002354 DSTFN     0000 R  002412 DSTMP     0000 R  002400 DSTTB     0000 R  000360 DTDZ1     0000 R  000372 DTDZ2
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 0002 R 001110 DXI       0002   001053 DXIMP    0002   001052 DXITB     0004   003464 DXX2     0004   003472 DXX21
 0000 R 000000 DY1       0002 R 001051 DZ       0004   003463 DZMFN     0004   003410 EBFN     0004   003441 EBMP
 0003 R 000000 ELEV      0000 R 002463 ENTHE    0000 R 002462 ENTHI     0004 R 003467 EXTIFN   0004   003471 EXTIMP
 0004 R 003466 EXTSFN    0004   003470 EXTSMP   0002 R 001103 FENTH     0002   001045 FFO      0007 R 000456 FLDINT
 0006   000016 FLMASS    0002 R 001101 FLUX     0010   000001 FLUXI     0002   001041 FMACH    0000 R 002470 FNM
 0002   001040 FNU       0002   001046 FOF      0002 R 000012 FP        0002   001042 FPR      0000 R 000404 FPRME
 0000 R 002451 FPRM1     0000 R 002450 FPRM2    0002   001037 FR        0002   001050 FRAD     0002   001111 FRD
 0002   001036 FRE       0002 R 001104 FREJ     0002   001043 FRL       0002   001044 FRM      0002 R 000036 FT
 0002 R 000024 FW        0002   001113 FXHW     0002   001112 FXOH      0002   001047 FZ       0015 R 000000 HFL
 0002 R 001105 HFN       0000 I 002432 I        0002   001003 IFLOW     0000 I 002465 IM2      0000   003361 INJP$
 0000 I 002442 J         0000 I 002443 K        0002   001024 LC        0004   003461 LCT      0007 I 000001 LFLD
 0002 I 001032 LIM       0002 I 001031 LIMWRT   0002   001011 LL1       0002   001012 LL2      0002   001013 LL3
 0002 I 001014 LL4       0002 I 001015 LL5      0002   001016 LL6       0002   001017 LL7      0002   001006 LMP
 0000 I 002500 LSKIP     0002 I 001004 LT       0002 I 001005 LTB       0002   001007 LTBMZ    0002   001010 LTB2MZ
 0004   003462 LTT       0004   003460 MCVRD    0002   001030 MM1       0002 I 001033 MOD      0002 I 001025 MSTOTR
 0002 I 000777 MZ        0002   001034 NCCZ     0002 I 001035 NCONV     0002   001002 NCTL     0002 I 001026 NCTM
 0002 I 001023 NEQUS     0007   000000 NFLDTA   0002   001027 NM1       0002 I 001001 NRMP     0002   001020 NRMP1
 0002   001022 NRMP2     0002   001000 NRTB     0002   001021 NRTB1     0005   001605 NSRD     0006 I 000012 NTBS
 0005   001604 NTM       0002 I 000776 NX       0002   001063 PHIF      0002   001062 PHIM     0002   001071 PI
 0006 R 000015 PLMASS    0002 R 001065 PO       0000 R 002445 QAERO     0005   000454 QIFN     0000 R 002425 QIRED
 0005   001274 QITB      0002 R 001102 QREF     0002 R 000360 QRFN      0002 R 000524 QRMP     0005   000144 QSFN
 0000 R 002424 QSOLR     0005   000764 QSTB     0005 R 001606 QTO       0000 R 002444 QTOT     0002 R 001074 RDTWRT
 0002 R 001114 RHOFN     0002 R 001067 RHOO     0002 R 001073 RLIMIT    0000 R 002461 RRR      0002 R 001100 RTEND
 0006 R 000000 SFN       0004   003473 SS       0000 R 002471 STFN      0000 R 002366 STFNX    0000 R 002475 STMP
 0000 R 002477 STORG     0006 R 000017 STR      0000 R 002473 STTB      0000 R 002441 TABS     0003 R 000002 TATM
 0006 R 000014 TBMASS    0002 R 000132 TEMP     0000 R 002452 TFNX1     0000 R 002453 TFNX2    0000 R 002426 TFN1
 0000 R 002427 TFN2      0011 R 000000 THCFN    0002   001077 TI        0007   000146 TIFLD    0002   001076 TINTL
 0005   000000 TM        0007   000002 TMEFLD   0002 R 000276 TMP       0006 R 000013 TNXL     0002 R 001075 TREF
 0004   000000 TRMTX     0000 R 002466 TT       0000 R 002457 TTT       0002 R 000050 TW       0000 R 002440 TWRTE
 0005   001607 TX        0002 R 001064 TO       0003 R 000001 VELS      0000 R 002435 W        0007   000312 WIFLD
 0010 R 000000 WRAT      0000 R 002460 WWW      0000 R 002447 WWX       0002 R 001066 WO       0002 R 000536 XIFN
 0002   000005 XIMP      0002   000000 XITB     0002 R 001106 XL        0000 R 002476 XLTW     0002   001054 XRE
 0000 R 001370 XTIME     0002   001057 XX10     0002   001060 XX11      0002   001061 XX12     0004   003446 XX2
 0002   001055 XX3       0002   001056 XX4      0014 R 000000 YINT      0000 R 002434 Z        0000 R 002436 ZCK
 0000 R 002433 ZE        0002 R 000550 ZETA     0000 R 002437 ZT        0004   003453 ZZ2
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```
00101              SUBROUTINE CNTLM(Y,DY,DX,X,NTRY,IFVD)
00101        C
00101        C    THIS SUBROUTINE :
00101        C      1- CONTROLS MAIN INTEGRATION
00101        C      2- CONTROLS OUTPUT OF MAIN INTEGRATION
00101        C      3- PROVIDES SYSTEM PERFORMANCE CHARACTERISTICS
00101        C    IS PART OF RKS AND DERIVM SUBROUTINES
00101        C
00103              COMMON XITB(5),XIMP(5),FP(10),FW(10),FT(10),TW(10,5),TEMP(10,10),
00103             1        TMP(10,5),QRFN(10,10),QRMP(10),XIFN(10),ZETA(10),AUX2(10),
00103             2        CONFN(10,10),CONMP(10),COB(10),DOB(10)
00104              COMMON NX,MZ,NRTB,NRMP,NCTL,IFLOW,LT,LTB,LMP,LTBMZ,LTB2MZ,LL1,
00104             1      LL2,LL3,LL4,LL5,LL6,LL7,NRMP1,NRTB1,NRMP2,NEQUS,LC,MSTOTR,
00104             2      NCTM,NM1,MM1,LIMWRT,LIM,MOD,NCCZ,NCONV
00105              COMMON FRE,FR,FNU,FMACH,FPR,FRL,FRM,FFO,FOF,FZ,FRAD,DZ,DXITB,DXIMP
00105             1        ,XRE,XX3,XX4,XX10,XX11,XX12,PHIM,PHIF,TO,PO,WO,RHOO,CPO,PI
00105             2        ,DELTA,RLIMIT,RDTWRT,TREF,TINTL,TI,RTEND,FLUX,QREF,FENTH,
00105             3        FREJ,HFN,XL,COH,DXI,FRD,FXOH,FXHW,RHOFN
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00106         COMMON /SRTCNV/ ELEV,VELS,TATM
00107         COMMON /QRD/ TRMTX(30,60),EBFN(5,5),EBMP(5),XX2(5),ZZ2(5),
00107        1             MCVRD,LCT,LTT,DZMFN,
00107        2             DXX2,CSF,EXTSFN,EXTIFN,EXTSMP,EXTIMP,DXX21,SS(5,5,5)
00110         COMMON /QIN/TM(100), QSFN(100,2), QIFN(100,2), QSTB(100,2),
00110        1            QITB(100,2), NTM, NSRD, QTO, TX
00111         COMMON /GEOM/ SFN(10),NTBS,TNXL,TBMASS,PLMASS,FLMASS,STR
00112         COMMON /FLDINL/ NFLDTA,LFLD,TMEFLD(100),TIFLD(100),WIFLD(100),
00112        1                FLDINT
00113         COMMON /DVCMFL/ WRAT,FLUXI
00113   C
00114         DIMENSION Y(200),DY(200),DY1(200),AUX1(10),AUX3(10),AUX4(10),
00114        1          AUX5(10),DTDZ1(10),DTDZ2(10),FPRME(500),XTIME(500)
00115         DIMENSION DSTFN(10),STFNX(10),DSTTB(10),DSTMP(10)
00115   C
00116         QSOLR   = EXTSFN*QTO
00117         QIRED   = EXTIFN*QTO
00117   C
00120         NCTM    = NCTM+1
00120   C
00121         TFN1    = TEMP(1,1)*T0
00122         TFN2    = TEMP(MZ,1)*T0
00123         ASTR1   = STR*SQRT(THCFN(TFN1)*CPFN(TFN1))
00124         ASTR2   = STR*SQRT(THCFN(TFN2)*CPFN(TFN2))
00125         IF (NCTM .GT. 500) GO TO 7
00125   C
00127         IF (X .LT. XTIME(NCTM-1)) GO TO 2
00131         FPRME(NCTM)   = ASTR1*DY(1)+ASTR2*DY(MZ)
00132         XTIME(NCTM)   = X
00133         GO TO 3
00134       2 FPRME(NCTM)   = FPRME(NCTM-1)
00135         XTIME(NCTM)   = XTIME(NCTM-1)
00136         FPRME(NCTM-1) = ASTR1*DY(1)+ASTR2*DY(MZ)
00137         XTIME(NCTM-1) = X
00137   C
00140       3 IF (NCTM .GT. 1) GO TO 5
00142         FPRME(NCTM) = ASTR1*DY(1)+ASTR2*DY(MZ)
00143         XTIME(NCTM) = X
00143   C
00144       7 IF (NCTM .GT. 1) GO TO 5
00146         DO 4  I = 1,NEQUS
00151       4 DY1(I)  = DY(I)
00153         GO TO 500
00154       5 IF(IFVD.EQ.1) GO TO 10
00156         IF(NTRY.EQ.3) GO TO 30
00160         GO TO (50,100),MSTOTR
00160   C
00161      10 IF(MSTOTR.EQ.1) GO TO 20
00163         ZE        = X-RTEND
00164         IF(ABS(ZE)/RDTWRT.LE.0.0005) GO TO 65
00166         IF(ZE.GT.0.0) GO TO 105
00170      15 IFVD      = 1
00171         DX        = RDTWRT
00172         IF(LIM.GT.LIMWRT) RETURN
00174         GO TO 500
00175      20 Z         = 0.0
00176         DO 25 I = 1,NEQUS
```

```
00201          IF(ABS(DY(I)).LT.1.0E-30) GO TO 25
00203          W       = ABS(DY1(I)/DY(I))
00204          IF(W.LE.0.0) GO TO 25
00206          ZCK     = ALOG(W)
00207          IF(ABS(ZCK).LT.1.0E-06) GO TO 25
00211          Z       = AMAX1(Z,ABS(DY(I)/ZCK)*DX)
00212       25 DY1(I)  = DY(I)
00214          IF(Z.LE.RLIMIT) GO TO 65
00216          IF(LIM.LE.LIMWRT) GO TO 15
00220          IFVD    = 0
00221          RETURN
00222       30 NTRY    = 1
00223          IF(MOD.EQ.1) GO TO 10
00225          GO TO 500
00225    C
00225    C
00226       50 Z       = 0.0
00227          DO 55 I = 1,NEQUS
00232          IF(ABS(DY(I)).LT.1.0E-30) GO TO 55
00234          W       = ABS(DY1(I)/DY(I))
00235          IF(W.LE.0.0) GO TO 55
00237          ZCK     = ALOG(W)
00240          IF(ABS(ZCK).LT.1.0E-06) GO TO 55
00242          Z       = AMAX1(Z,ABS(DY(I)/ZCK)*DX)
00243       55 DY1(I)  = DY(I)
00245          IF(Z.LE.RLIMIT) GO TO 65
00247          GO TO 70
00247    C
00250       65 NTRY    = 2
00251          GO TO 505
00251    C
00252       70 IF(LIM.GT.LIMWRT) RETURN
00254          ZT      = X-TWRTE
00255          IF(ABS(ZT)/RDTWRT.LE.0.0005) GO TO 500
00257          IF(ZT.LT.0.0) RETURN
00261          NTRY    = 3
00262          IF(DX.GE.RDTWRT) MOD = 1
00264          DX      = DX+TWRTE-X
00265          RETURN
00265    C
00266      100 ZE      = X-RTEND
00267          IF(ABS(ZE)/RDTWRT.LT.0.0005) GO TO 65
00271          IF(ZE.LT.0.0) GO TO 70
00273      105 NTRY    = 3
00274          DX      = DX+RTEND-X
00275          RETURN
00275    C
00275    C
00276      500 TWRTE   = X+RDTWRT
00277      505 TABS    = X+TREF
00300          IF(NCONV.GT.0) GO TO 506
00302          WRITE(6,510) TABS,X,NCTM
00307          GO TO 507
00310      506 WRITE(6,509) TABS,X,NCTM,ELEV,VELS,TATM
00310    C
00310    C
00320      507 DO 508 J=1,MZ
```

```
00323            FT(J)    = Y(LT+J)
00324            TW(J,1)      = Y(LTB+J)
00325            TMP(J,NRMP) = Y(LL5+J)
00326            TEMP(J,1)   = Y(LL4+J)
00327            DO 508 I=2,NX
00332            K              = MZ*(I-2)+J
00333        508 TEMP(J,I)    = Y(K)
00336            IF (LFLD .EQ. 2) FT(1) = FLDINT
00336      C
00336      C
00340        509 FORMAT(1H1,5X,20HELAPSED TIME IS      ,F12.4,6H HR , ,
00340           1          6X,20HRELATIVE TIME IS     ,F12.4,
00340           2          6X,I7,14H INTEGR. STEPS,/,
00340           3          6X,20HALTITUDE IS          ,F10.2,8H   FT , ,
00340           4          6X,20HVELOCITY IS          ,F10.2,10H FT/SEC , ,
00340           5          6X,22HATM. TEMPERATURE IS   ,F8.2,2H R,/)
00341        510 FORMAT(1H1,5X,25HELAPSED TIME IS           ,F12.4,11H HR        ,/,
00341           1          6X,25HRELATIVE TIME IS          ,F12.4,
00341           2          18X,12H**IN ORBIT**,20X,I7,14H INTEGR. STEPS,/)
00341      C
00341      C     LISTING OF FIN TEMPERATURE DISTRIBUTION
00341      C
00342            DO 512 J=1,MZ
00345            DO 511 I=1,NX
00350            AUX4(I) = CONFN(J,I)
00351        511 AUX1(I) = QRFN(J,I)
00353            AUX5(J) = DEFINT(AUX4,DXI,NX)+CONMP(J)*COH
00354        512 AUX3(J) =  DEFINT(AUX1,DXI,NX)+QRMP(J)*COH
00356            QTOT     = DEFINT(AUX3,DZ,MZ)*QREF*XL
00357            QAERO    = DEFINT(AUX5,DZ,MZ)*QREF*XL
00357      C
00357      C     CONDUCTION FROM MANIFOLD
00357      C
00360            IF (NCTM .GT. 500) GO TO 514
00362            IF (NCTM .GT. 3) GO TO 513
00364            CONDMF   = 0.66667*FPRME(1)*SQRT(XTIME(NCTM))
00365            GO TO 600
00366        513 WWX      = X/3.0
00367            FPRM2    = YINT(XTIME,FPRME,NCTM,3,WWX)
00370            WWX      = 2.0*WWX
00371            FPRM1    = YINT(XTIME,FPRME,NCTM,3,WWX)
00372            CONDMF   = SQRT(XTIME(NCTM))/105.0*(68.0*FPRME(NCTM)+90.0*FPRM1+
00372           1           36.0*FPRM2+16.0*FPRME(1))
00372      C
00373        514 DO 580 I=1,NX
00376            TFNX1     = TEMP(1,I)*T0
00377            DTDZ1(I)  = -THCFN(TFNX1)*SFN(I)*(-3.0*TEMP(1,I)+4.0*TEMP(2,I)
00377           1             -TEMP(3,I))
00400            TFNX2     = TEMP(MZ,I)*T0
00401        580 DTDZ2(I)  = THCFN(TFNX2)*SFN(I)*(3.0*TEMP(MZ,I)-4.0*TEMP(MZ-1,I)+
00401           1             TEMP(MZ-2,I))
00403            COND1     = DEFINT(DTDZ1,DXI,NX)
00404            COND2     = DEFINT(DTDZ2,DXI,NX)
00405            CONMF1    = (COND1+COND2)*NTBS*T0*HFN/(DZ*XL)
00406            IF (CONDMF .LE. CONMF1 .OR. NCTM .GT. 500) CONDMF = CONMF1
00406      C
00406      C     FLUID ENTHALPY REJECTION
```

```
00406        C
00410          600 TTT      = FT(1)*T0
00411              WWW      = FW(1)*W0
00412              RRR      = RHO0/FW(1)
00413              ENTHI    = FLUX*(HFL(RRR,TTT)+WWW**2/1556.36)*WRAT
00414              TTT      = FT(MZ)*T0
00415              WWW      = FW(MZ)*W0
00416              RRR      = RHO0/FW(MZ)
00417              ENTHE    = FLUX*(HFL(RRR,TTT)+WWW**2/1556.36)*WRAT
00420              DENTH    = ENTHI-ENTHE
00420        C
00420        C     ENERGY STORAGE RATE
00420        C
00420        C     FIN
00420        C
00421              DO 700 I=2,NX
00424              IM2      = I-2
00425              DO 700 J=1,MZ
00430              K        = IM2*MZ+J
00431              TT       = T0*TEMP(J,I)
00432              CPFN1    = CPFN(TT)
00433              DSTFN(J)= CPFN1*SFN(I)*DY(K)
00434          700 STFNX(I)= DEFINT(DSTFN,DZ,MZ)
00437              DO 705 J=1,MZ
00442              K        = LTB+J
00443              TT       = T0*TEMP(J,1)
00444              CPFN1    = CPFN(TT)
00445              DSTFN(J)= CPFN1*DY(K)
00446          705 STFNX(1)= DEFINT(DSTFN,DZ,MZ)*SFN(1)
00450              FNM      = 2.0*RHOFN*TNXL*HFN
00451              STFN     = DEFINT(STFNX,DXI,NX)*FNM
00451        C
00451        C     TUBE
00451        C
00452              DO 710 J=1,MZ
00455              K        = LTB+J
00456              TT       = T0*TEMP(J,1)
00457              CPTB1    = CPTB(TT)
00460          710 DSTTB(J)= CPTB1*DY(K)
00462              STTB     = DEFINT(DSTTB,DZ,MZ)*TBMASS
00462        C
00462        C     PROTECTION LAYER
00462        C
00463              DO 715 J=1,MZ
00466              K        = LTB+J
00467              TT       = T0*TEMP(J,1)
00470              CPMP1    = CPMP(TT)
00471          715 DSTMP(J)= CPMP1*DY(K)
00473              STMP     = DEFINT(DSTMP,DZ,MZ)*PLMASS
00473        C
00474              XLTW     = XL/(T0*W0*3600.0)
00475              STORG    = (STFN+STTB+STMP)/XLTW
00476              STORG    = DENTH+CONDMF+QAERO-QTOT
00476        C
00477              WRITE(6,515) T0,QSOLR,QREF,QIRED,QTOT,QAERO,CONDMF,STORG,
00477             1(XIFN(I),I=1,NX)
00515          515 FORMAT(1H0,15X,55HFIN TEMPERATURE DISTRIBUTION AND RADIANT HEAT RE
```

```
00515        1JECTION,/,16X,55H*******************************************************
00515        2******,//,
00515        3 2X,33HREFERENCE TEMPERATURE,      TOO  =,F10.3,13H R          ,/,
00515        4 2X,56HREF. RADIANT HEAT FLUX                                  ,
00515        5 8X,33HINCIDENT SOLAR FLUX,      QSOLR. =,E10.4,15H BTU/(HR SQ FT),
00515        6 /,
00515        7 2X,33H   PER UNIT AXIAL LENGTH, QREF  =,E10.4,13H BTU/(HR FT),
00515        8 8X,33HINCIDENT INFRARED FLUX,  QIRED  =,E10.4,15H BTU/(HR SQ FT),
00515        9 /,
00515        1 2X,33HTOT. RADIANT REJECTION    QTOT  =,E10.4,13H BTU/HR      ,
00515        2 8X,33HAERODYN. HEATING POWER,  QCONV  =,E10.4,7H BTU/HR,/,
00515        3 2X,33HCOND. FROM MANIFOLDS,   CONDMF  =,E10.4,13H BTU/HR      ,
00515        4 8X,33HENERGY STORAGE RATE,     STORG  =,E10.4,7H BTU/HR,//
00515        5/,6H AXIAL,4X,8HRELATIVE,14X,30HRELATIVE TEMPERATURE OF FIN, T,/,6
00515        6H DIST.,4X,9HRAD. HEAT,/,10X,9HREJECTION,15X,33HDISTANCE NORMAL TO
00515        7 FLOW DIRECTION,/,3H  Z,9X,1HQ,31X,1HX,/,20X,10F9.5,)
00516         WRITE(6,516)
00520    516 FORMAT(1H ,120H-----------------------------------------------------
00520        1-----------------------------------------------------------------
00520        2---)
00521         DO 525 J=1,MZ
00524    525 WRITE(6,530) ZETA(J),AUX3(J),(TEMP(J,I),I=1,NX)
00535    530 FORMAT(1H ,F5.3,F11.4,2X,10F9.4)
00536         WRITE(6,555)
00536  C
00540         WRITE(6,535) TO,PO,WO,FENTH,ENTHI,ENTHE,DENTH
00551    535 FORMAT(1HO,15X,70HFLUID PROPERTIES AND SURFACE TEMPERATURE OF METE
00551        1OROID PROTECTION LAYER,/,16X,70H**********************************
00551        2************************************,//,
00551        3 10X,33HREFERENCE TEMPERATURE, TOO       =,F15.3,12H R          ,/,
00551        4 10X,33HREFERENCE PRESSURE,    POO       =,F15.3,12H LBF/SQ.FT  ,/,
00551        5 10X,33HREFERENCE VELOCITY,    WOO       =,F15.3,12H FT/SEC     ,/,
00551        6 6X,36HCOOLANT POWER, INLET  AT T=TO  HO = ,E11.6,7H BTU/HR,
00551        7 6X,36H                INLET CURRENTLY  HI = ,E11.6,7H BTU/HR,/,
00551        8 6X,36H                EXIT  CURRENTLY  EI = ,E11.6,7H BTU/HR,
00551        9 6X,36H                TOT. REJECTION   DH = ,E11.6,7H BTU/HR,//
00551        9 58X,8HPROTECT.,10X,18HENTHALPY REJECTION,/,36X,5HFLUID,7X,4HWALL,
00551        17X,5HLAYER,7X,13HPER UNIT TUBE,5X,8HFRACTION,/,6H AXIAL,5X,8HPRESS
00551        2URE,4X,8HVELOCITY,9X,23HT E M P E R A T U R E S,12X,6HLENGTH,11X,2
00551        3HOF,/,6H DIST.,8X,1HP,11X,1HW,11X,2HTF,9X,3HTWI,9X,3HTMP,9X,
00551        411HBTU/(HR FT),7X,5HTOTAL,/)
00551  C
00551  C      POWER FLUX, FLUID FLOW
00551  C
00552         LSKIP   = 1
00553         CALL FINT(AUX2,0.0,DZ,MZ,AUX1)
00554         DEDT    = AUX1(1)-AUX1(MZ)
00555         IF(ABS(DEDT).LT.1.0E-08) LSKIP = 2
00557         DO 545 J=1,MZ
00562         DEDOT   = 0.0
00563         GO TO (543,544), LSKIP
00564    543 DEDOT   = (AUX1(1)-AUX1(J))/DEDT
00565    544 DIFE    = AUX2(J)*FREJ
00566    545 WRITE(6,550) ZETA(J),FP(J),FW(J),FT(J),TW(J,1),TMP(J,NRMP),DIFE,
00566        1            DEDOT
00601    550 FORMAT(1H ,F5.3,F12.5,F11.4,3F12.4,F17.6,F14.5)
00602         WRITE(6,555)
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00604           555 FORMAT(1H ,7H (EXIT))
00604         C
00605               LIM     = LIM+1
00606               IF (MSTOTR .EQ. 1 .AND. NTRY .EQ. 2) WRITE (6,560)
00611           560 FORMAT (1H1,25H  STEADY STATE IS REACHED)
00612               RETURN
00613               END

        END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  CNTLN  ******
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@FOR,S ME*NASA5.CNTLN,ME*NASA5.CNTLN
FOR S9A-07/13/72-20:54:26 (0,)

   SUBROUTINE CNTLN     ENTRY POINT 000075

   STORAGE USED: CODE(1) 000111; DATA(0) 000023; BLANK COMMON(2) 001115

    COMMON BLOCKS:

    0003   DRVLCM 000024
    0004   DRVLCN 000001

   EXTERNAL REFERENCES (BLOCK, NAME)

    0005   NWDU$
    0006   NI01$
    0007   NI02$
    0010   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000     000001 1F       0001     000025 120G     0002     000562 AUX2     0004 R 000000 B2       0002     000752 COB
    0002     001107 COH      0002     000574 CONFN    0002     000740 CONMP    0002     001070 CPO      0002     001072 DELTA
    0002     000764 DOB      0002     001110 DXI      0002     001053 DXIMP    0002     001052 DXITB    0002     001051 DZ
    0002     001103 FENTH    0002     001045 FFO      0002     001101 FLUX     0002     001041 FMACH    0002     001040 FNU
    0002     001046 FOF      0002 R 000012 FP       0002     001042 FPR      0002     001037 FR       0002     001050 FRAD
    0002     001111 FRD      0002     001036 FRE      0002     001104 FREJ     0002     001043 FRL      0002     001044 FRM
    0002 R 000036 FT       0002 R 000024 FW       0002     001113 FXHW     0002     001112 FXOH     0002     001047 FZ
    0002     001105 HFN      0000 I 000000 I        0002 I 001003 IFLOW    0000     000007 INJP$    0002     001024 LC
    0002     001032 LIM      0002     001031 LIMWRT   0002     001011 LL1      0002     001012 LL2      0002     001013 LL3
    0002     001014 LL4      0002     001015 LL5      0002     001016 LL6      0002     001017 LL7      0002     001006 LMP
    0002     001004 LT       0002     001005 LTB      0002     001007 LTBMZ    0002     001010 LTB2MZ   0002     001030 MM1
    0002     001033 MOC      0002     001025 MSTOTR   0002 I 000777 MZ       0002     001034 NCCZ     0002     001035 NCONV
    0002 I 001002 NCTL     0002     001026 NCTM     0002     001023 NEQUS    0002     001027 NM1      0002     001001 NRMP
    0002     001020 NRMP1    0002     001022 NRMP2    0002     001000 NRTB     0002     001021 NRTB1    0002     000776 NX
    0002     001063 PHIF     0002     001062 PHIM     0002     001071 PI       0002     001065 PO       0002     001102 QREF
    0002     000360 QRFN     0002     000524 QRMP     0002     001074 RDTWRT   0002     001114 RHOFN    0002     001067 RHOO
    0002     001073 RLIMIT   0002     001100 RTEND    0003 R 000000 STRGE1   0003 R 000012 STRGE2   0002     000132 TEMP
    0002     001077 TI       0002     001076 TINTL    0002     000276 TMP      0002     001075 TREF     0002 R 000050 TW
    0002     001064 TO       0002     001066 WO       0002     000536 XIFN     0002     000005 XIMP     0002     000000 XITB
    0002     001106 XL       0002     001054 XRE      0002     001057 XX10     0002     001060 XX11     0002     001061 XX12
    0002     001055 XX3      0002     001056 XX4      0002     000550 ZETA


 00101       1*           SUBROUTINE CNTLN (Y,DY,DXX,X,NTRY,IFVD)
 00101       2*      C
 00101       3*      C  THIS SUBROUTINE CONTROLS :
 00101       4*      C    1- INTEGRATION OF COOLANT FLUID PRESSURE AND VELOCITY FIELDS
 00101       5*      C    2- INTEGRATION FOR FLUID INITIAL CONDITIONS
 00101       6*      C  IS PART OF RKSF AND DERIVL SUBROUTINES
 00101       7*      C
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```
00103        COMMON XITB(5),XIMP(5),FP(10),FW(10),FT(10),TW(10,5),TEMP(10,10),
00103       1       TMP(10,5),QRFN(10,10),QRMP(10),XIFN(10),ZETA(10),AUX2(10),
00103       2       CONFN(10,10),CONMP(10),COB(10),DOB(10)
00104        COMMON NX,MZ,NRTB,NRMP,NCTL,IFLOW,LT,LTB,LMP,LTBMZ,LTB2MZ,LL1,
00104       1      LL2,LL3,LL4,LL5,LL6,LL7,NRMP1,NRTB1,NRMP2,NEQUS,LC,MSTOTR,
00104       2      NCTM,NM1,MM1,LIMWRT,LIM,MOD,NCCZ,NCONV
00105        COMMON FRE,FR,FNU,FMACH,FPR,FRL,FRM,FFO,FOF,FZ,FRAD,DZ,DXITB,DXIMP
00105       1       ,XRE,XX3,XX4,XX10,XX11,XX12,PHIM,PHIF,T0,P0,W0,RHO0,CP0,PI
00105       2       ,DELTA,RLIMIT,RDTWRT,TREF,TINTL,TI,RTEND,FLUX,QREF,FENTH,
00105       3       FREJ,HFN,XL,COH,DXI,FRD,FXOH,FXHW,RHOFN
00106        COMMON /DRVLCM/ STRGE1(10),STRGE2(10)
00107        COMMON /DRVLCN/ B2
00110        DIMENSION Y(3),DY(3)                                              04
00110   C
00111        STRGE1(NCTL) = B2
00112        STRGE2(NCTL) = DY(3)
00113        IF(IFLOW.EQ.1) WRITE (6,1) NCTL,X,(Y(I),I=1,3),TW(NCTL,1)
00125        IF(NCTL.EQ.MZ) NTRY=2
00127        FP(NCTL) = Y(1)                                                   08
00130        FW(NCTL) = Y(2)                                                   09
00131        IF (IFLOW .EQ. 1) FT(NCTL) = Y(3)
00133        NCTL = NCTL+1                                                     011
00134        RETURN                                                            012
00134   C
00135      1 FORMAT (15X,I5,F10.3,4F20.6)                                      014
00136        END                                                               015

       END OF COMPILATION:        NO  DIAGNOSTICS.


QHDG,P  ******  CONVEC  ******
```

```
@FOR,S ME*NASA5.CONVEC,ME*NASA5.CONVEC
FOR S9A-07/13/72-20:54:33 (0,)

   SUBROUTINE CONVEC     ENTRY POINT 000543

   STORAGE USED: CODE(1) 000561; DATA(0) 000144; BLANK COMMON(2) 001115

    COMMON BLOCKS:

    0003    VELALT 001132
    0004    CNV    000010
    0005    SRTCNV 000003
    0006    QRD    003721
    0007    SSF    000005

   EXTERNAL REFERENCES (BLOCK, NAME)

    0010    ALTVEL
    0011    ATMOS
    0012    ENTAIR
    0013    TNH
    0014    CPAIR
    0015    REFP
    0016    NUS
    0017    NEXP6$
    0020    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001    000031 122G      0001    000033 125G      0001    000425 150L      0001    000401 211G      0001    000416 220G
    0001    000417 223G      0001    000431 231G      0001    000507 243G      0001    000510 246G      0001    000122 31L
    0001    000236 35L       0001    000253 37L       0001    000267 47L       0001    000045 5L        0001    000277 51L
    0002    001105 AL        0007    000002 ALPFN     0003 R  000310 ALTA      0003 R  000454 ALTR      0010 R  000000 ALTVEL
    0002    000562 AUX2      0000 R  000020 CATM      0002    000752 COB       0000 R  000043 COEF      0004    000007 COEFF
    0002    001107 COH       0002 R  000574 CONFN     0002 R  000740 CONMP     0014 R  000000 CPAIR     0000 R  000054 CPFIN
    0000 R  000045 CPMP      0002    001070 CP0       0006    003465 CSF       0002    001072 DELTA     0002    000764 DOB
    0004    000003 DX        0002    001110 DXI       0002    001053 DXIMP     0002    001052 DXITB     0006    003464 DXX2
    0006    003472 DXX21     0002    001051 DZ        0006    003463 DZMFN     0006    003410 EBFN      0006    003441 EBMP
    0005 R  000000 ELEV      0012 R  000000 ENTAIR    0000 R  000021 ENTATM    0000 R  000042 ENTAW     0000 R  000030 ENTFN
    0006    003467 EXTIFN    0006    003471 EXTIMP    0006    003466 EXTSFN    0006    003470 EXTSMP    0002    001103 FENTH
    0002    001045 FFO       0002    001101 FLUX      0002    001041 FMACH     0002    001040 FNU       0002    001046 FOF
    0002    000012 FP        0002    001042 FPR       0002    001037 FR        0002    001050 FRAD      0002    001111 FRD
    0002    001036 FRE       0002    001104 FREJ      0002    001043 FRL       0002    001044 FRM       0002    000036 FT
    0002    000024 FW        0002    001113 FXHW      0002    001112 FXOH      0002    001047 FZ        0002    001105 HFN
    0000 I  000051 I         0002    001003 IFLOW     0000 I  000024 II        0000    000116 INJP$     0004 I  000002 IOPTN
    0000 I  000050 J         0000 I  000025 JJ        0000 I  000053 L         0002    001024 LC        0006    003461 LCT
    0002    001032 LIM       0002    001031 LIMWRT    0002    001011 LL1       0002    001012 LL2       0002    001013 LL3
    0002    001014 LL4       0002    001015 LL5       0002    001016 LL6       0002    001017 LL7       0002    001006 LMP
    0002    001004 LT        0002    001005 LTB       0002    001007 LTBMZ     0002    001010 LTB2MZ    0006    003462 LTT
    0000 I  000026 M         0000 R  000000 MACHNO    0006 I  003460 MCVRD     0000 I  000017 MM        0002    001030 MM1
    0002    001033 MOD       0002    001025 MSTOTR    0000 R  000002 MWT       0002 I  000777 MZ        0003 I  001130 NA
    0002    001034 NCCZ      0002    001035 NCONV     0002    001002 NCTL      0002    001026 NCTM      0002    001023 NEQUS
    0002    001027 NM1       0000 I  000016 NN        0003 I  001131 NR        0002 I  001001 NRMP      0002    001020 NRMP1
```

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0002   001022 NRMP2    0002   001000 NRTB     0002   001021 NRTB1    0004 I 000004 NSRAD    0000 R 000001 NUS1
0002 I 000776 NX       0002   001063 PHIF     0002   001062 PHIM     0002   001071 PI       0002   001065 PO
0002   001102 QREF     0002   000360 QRFN     0002   000524 QRMP     0002   001074 RDTWRT   0000 R 000031 RECFAC
0000 R 000037 REFCP    0000 R 000032 REFENT   0000 R 000023 REFGAM   0000 R 000036 REFK     0000 R 000022 REFPR
0000 R 000041 REFRHO   0000 R 000003 REFT     0000 R 000033 REFTP    0000 R 000035 REFVIS   0002   001114 RHOFN
0002   001067 RHOO     0002   001073 RLIMIT   0002   001100 RTEND    0007   000003 R1       0007   000000 R2
0004   000005 SMPC     0006   003473 SS       0006   003670 SSTT     0004 R 000000 STAGX    0004 R 000006 ST4
0007   000001 T        0003 R 000000 TA       0005 R 000002 TATM     0002 R 000132 TEMP     0000 R 000052 TFIN
0004   000005 THICK    0002   001077 TI       0002 R 001064 TIN      0002   001076 TINTL    0000 R 000044 TMET
0000 R 000034 TMK      0002 R 000276 TMP      0000 R 000027 TMPE     0013 R 000000 TNH      0003 R 000144 TR
0002   001075 TREF     0006   000000 TRMTX    0002   000050 TW       0002   001064 TO       0003 R 000620 VELA
0003 R 000764 VELR     0005 R 000001 VELS     0004 R 000001 VERTX    0002   001066 WO       0002   000536 XIFN
0002   000005 XIMP     0002   000000 XITB     0002   001106 XL       0002   001054 XRE      0007 R 000004 XSPM
0000 R 000046 XXX      0002   001057 XX10     0002   001060 XX11     0002   001061 XX12     0006   003446 XX2
0002   001055 XX3      0002   001056 XX4      0000 R 000047 YYY      0000 R 000040 Z        0002   000550 ZETA
0000 R 000055 ZZZ      0006   003453 ZZ2
```

```
00101          SUBROUTINE CONVEC (TIME)
00101    C
00101    C   THIS SUBROUTINE COMPUTES :
00101    C     CONVECTIVE HEAT FLUX ON THE RADIATOR SYSTEM OF THE SHUTTLE
00101    C     DURING EITHER ASCENT OR REENTRY
00101    C
00103          COMMON XITB(5),XIMP(5),FP(10),FW(10),FT(10),TW(10,5),TEMP(10,10),
00103         1        TMP(10,5),QRFN(10,10),QRMP(10),XIFN(10),ZETA(10),AUX2(10),
00103         2        CONFN(10,10),CONMP(10),COB(10),DOB(10)
00104          COMMON NX,MZ,NRTB,NRMP,NCTL,IFLOW,LT,LTB,LMP,LTBMZ,LTB2MZ,LL1,
00104         1       LL2,LL3,LL4,LL5,LL6,LL7,NRMP1,NRTB1,NRMP2,NEQUS,LC,MSTOTR,
00104         2       NCTM,NM1,MM1,LIMWRT,LIM,MOD,NCCZ,NCONV
00105          COMMON FRE,FR,FNU,FMACH,FPR,FRL,FRM,FFO,FOF,FZ,FRAD,DZ,DXITB,DXIMP
00105         1        ,XRE,XX3,XX4,XX10,XX11,XX12,PHIM,PHIF,TO,PO,WO,RHOO,CPO,PI
00105         2        ,DELTA,RLIMIT,RDTWRT,TREF,TINTL,TI,RTEND,FLUX,QREF,FENTH,
00105         3        FREJ,HFN,XL,COH,DXI,FRD,FXOH,FXHW,RHOFN
00106          COMMON/VELALT/TA(100),TR(100),ALTA(100),ALTR(100),VELA(100),
00106         1             VELR(100),NA,NR
00107          COMMON/CNV/STAGX,VERTX,IOPTN,DX,NSRAD,SMPC,ST4,COEFF
00110          COMMON /SRTCNV/ ELEV,VELS,TATM
00111          COMMON /QRD/ TRMTX(30,60),EBFN(5,5),EBMP(5),XX2(5),ZZ2(5),
00111         1            MCVRD,LCT,LTT,DZMFN,
00111         2            DXX2,CSF,EXTSFN,EXTIFN,EXTSMP,EXTIMP,DXX21,SS(5,5,5)
00111         3            ,SSTT(5,5)
00112          COMMON /SSF/R2, T, ALPFN,R1,XSPM
00113          EQUIVALENCE (SMPC,THICK),(TIN,TO),(AL,HFN)
00114          REAL MACHNO,NUS1,MWT
00115          DIMENSION REFT (11)
00116          ELEV   = ALTVEL(TIME,IOPTN,ALTA,ALTR,TA,TR,NA,NR)
00117          IF (ELEV .LT. 528000.)  GO TO  5
00121          DO 2 NN = 1,NX
00124          DO 2 MM = 1,MZ
00127          CONMP(MM)      =  0.0
00130        2 CONFN(MM,NN)   =  0.0
00133          RETURN
00134        5 VELS   = ALTVEL(TIME,IOPTN,VELA,VELR,TA,TR,NA,NR)
00135          CALL ATMOS (ELEV,TATM,CATM)
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00136          ENTATM  =  ENTAIR(TATM)
00137       20 MACHNO =  VELS/CATM
00140          REFPR   =  0.72
00141          REFGAM  =  1.3
00142          II      = MZ/2
00143          JJ      =  NX/2
00144          M       =  1
00145          TMPE    =  TEMP(II,JJ)*TIN
00146          ENTFN   =  ENTAIR(TMPE)
00147       31 RECFAC =  REFPR**((8.0+0.528*MACHNO**2)/(22.0+MACHNO**2))
00150       33 REFENT  =  0.5*(ENTATM+ENTFN)+0.11*RECFAC*
00150        1             (REFGAM-1.0)*MACHNO**2*ENTATM
00151          REFT(M) =  TNH(REFENT)
00152          REFTP   =  REFT(M)
00153          TMK     =  REFTP/1.8
00154          REFVIS =  ((1.458E-06*TMK**1.5)/(TMK+110.4))*0.671969
00155          REFK    = ((6.325E-07*TMK**1.5)/(TMK+245.4*10.0**(-12.0/TMK)))
00155        1           *0.671969
00156          REFCP   =  CPAIR(REFTP)
00157          REFPR  =  REFVIS*REFCP/REFK
00160          IF (ELEV .GT. 301000.)  GO TO 35
00162          REFGAM  =  REFCP/(REFCP-0.0686)
00163          GO TO 37
00164       35 Z       =  ELEV/(3280.8399)
00165          MWT     =  28.9644-0.0309491*(Z-90.0)
00166          REFGAM  =  REFCP/(REFCP-(1.98585/MWT))
00167       37 IF (M .EQ. 1)  GO TO 47
00171          IF (ABS(REFT(M)-REFT(M-1)) .LE. 5.0)  GO TO 51
00173       47 M       =  M+1
00174          IF (M .GT. 10) GO TO  51
00176          GO TO 31
00177       51 CONTINUE
00200          CALL REFP (ELEV,REFTP,REFPR,REFVIS,REFRHO,REFK,REFCP,
00200        1             REFGAM)
00201          ENTAW   =  ENTATM+RECFAC*VELS**2/50062.744
00202          CALL NUS(MACHNO,TATM,CATM,TIN,REFPR,REFVIS,REFRHO,
00202        1          STAGX,VERTX,NSRAD,NUS1)
00203          COEF    =  (3600.*REFK)/(STAGX*REFCP)
00203     C
00203     C DETERMINATION OF CONVECTION LOSS FROM METEOROID PROTECTION NODES
00203     C
00204          TMET    = TMP(II,NRMP)*TIN
00205          CPMP    = CPAIR(TMET)
00206          XXX     =  COEF*NUS1
00207          YYY     =  CPMP*TIN
00210          DO 80 J = 1,MZ
00213       80 CONMP(J)   =  XXX*(ENTAW-YYY*TMP(J,NRMP))/(ST4*2.)
00213     C
00213     C DE3ERMINATION OF FRACTION OF FIN NODES COVERED BY PROTECTION LAYER
00213     C
00215          IF (MCVRD .EQ. 0)  GO TO 150
00217          DO 140 I = 1,MCVRD
00222          DO 140 J = 1,MZ
00225      140 CONFN(J,I)  =  0.0
00230      150 DO 160 J = 1,MZ
00233          TFIN    =  TEMP(J,MCVRD+1)*TIN
00234          ENTFN   =  ENTAIR(TFIN)
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```
00235        160 CONFN(J,MCVRD+1)  =  XSPM*COEF*NUS1*(ENTAW-ENTFN)/ST4
00237            L        =  MCVRD+2
00237       C
00237       C DETERMINATION OF CONVECTION LOSS FROM FIN NODES
00237       C
00240            CPFIN  =  CPAIR(TMPE)
00241            ZZZ    =  CPFIN*TIN
00242            DO 180 I = L,NX
00245            DO 180 J = 1,MZ
00250        180 CONFN(J,I)  =  XXX*(ENTAW-ZZZ*TEMP(J,I))/ST4
00253       1000 RETURN
00254            END

        END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  CPAIR  ******
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```
****** CPAIR ******                                                                    DATE 071372        PAGE      1

@FOR,S ME*NASA5.CPAIR,ME*NASA5.CPAIR
FOR S9A-07/13/72-20:54:38 (0,)

   FUNCTION CPAIR       ENTRY POINT 000074

   STORAGE USED: CODE(1) 000110; DATA(0) 000035; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   POLY
    0004   SQRT
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000054 10L        0001   000016 5L         0000 R 000001 A          0000 R 000000 CPAIR      0000 R 000012 CPN
    0000 R 000013 CPO        0000 R 000007 FMN        0000 R 000006 FMO        0000   000027 INJP$      0003 R 000000 POLY
    0000 R 000011 WMN        0000 R 000010 WMO



00101         FUNCTION CPAIR(T)
00101   C
00101   C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101   C        THE SPECIFIC HEAT OF AIR AS A FUNCTION OF TEMPERATURE (R)
00101   C                                        UNITS BTU/(LBM.R)
00101   C
00103         DIMENSION A(5)
00104         DATA FMO,FMN,WMO,WMN / 0.234559 ,0.765441,31.9988,28.0134/
00111         DATA A(1),A(2),A(3),A(4),A(5)/0.34240E+00,-0.95225E-03,
00111        1     0.31862E-05,-0.45750E-08,0.23750E-11/
00117         IF (T .GT. 600.) GO TO 5
00121         CPAIR    =  POLY (5,A,T)
00122         RETURN
00123       5 CPN      =  9.47-3470./T+1160000./T**2
00124         CPO      =  11.151-172./SQRT(T)+1530./T
00125         IF (T .LT. 5000.) GO TO 10
00127         CPO      =  CPO+5.0E-05*(T-4000.)
00130      10 CPAIR    =  FMO*CPO/WMO+FMN*CPN/WMN
00131         RETURN
00132         END

      END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  CPF/CFFC43  ******
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```
****** CPF/CFFC43 ******                                                              DATE 071372        PAGE    1

@FOR,S ME*NASA5.CPF/CFFC43,ME*NASA5.CPF/CFFC43
FOR S9A-07/13/72-20:54:41 (0,)

    FUNCTION CPF        ENTRY POINT 000014

    STORAGE USED: CODE(1) 000016; DATA(0) 000011; BLANK COMMON(2) 000000

    EXTERNAL REFERENCES (BLOCK, NAME)

     0003   NERR3$

    STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

     0000 R 000000 CPF       0000   000004 INJP$     0000 R 000001 X1        0000 R 000002 X2


00101      1*           FUNCTION CPF(RHO,T)
00101      2*     C
00101      3*     C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*     C        SPECIFIC HEAT AT CONSTANT PRESSURE AS A FONCTION OF
00101      5*     C             DENSITY (SLUG/CU.FT) AND TEMPERATURE (R) OF FC-43
00101      6*     C                                     UNITS BTU/(SLUG.R)
00101      7*     C
00103      8*           DATA X1,X2 /-0.020092,5.4054E-04/
00106      9*           CPF = (X1+X2*T)*32.174
00107     10*           RETURN
00110     11*           END

       END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  CPF/CFFC75  ******
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****** CPF/CFFC75 ******                                                      DATE 071372        PAGE    1

@FOR,S ME*NASA5.CPF/CFFC75,ME*NASA5.CPF/CFFC75
FOR S9A-07/13/72-20:54:43 (0,)

   FUNCTION CPF          ENTRY POINT 000014

   STORAGE USED: CODE(1) 000016; DATA(0) 000011; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000000 CPF       0000    000004 INJP$     0000 R 000001 X1        0000 R 000002 X2


00101       1*           FUNCTION CPF(RHO,T)
00101       2*     C
00101       3*     C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101       4*     C        SPECIFIC HEAT AT CONSTANT PRESSURE AS A FONCTION OF
00101       5*     C             DENSITY (SLUG/CU.FT) AND TEMPERATURE (R) OF FC-75
00101       6*     C                                     UNITS BTU/(SLUG.R)
00101       7*     C
00103       8*           DATA X1,X2 /0.115082,2.4333E-04/
00106       9*           CPF = (X1+X2*T)*32.174
00107      10*           RETURN
00110      11*           END

      END OF COMPILATION:        NO  DIAGNOSTICS.

@HDG,P  ******  CPF/CFHE  ******
```

```
@FOR,S ME*NASA5.CPF/CFHE,ME*NASA5.CPF/CFHE
FOR S9A-07/13/72-20:54:45 (0,)

   FUNCTION CPF        ENTRY POINT 000057

   STORAGE USED: CODE(1) 000071; DATA(0) 000031; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   BETA
    0004   CAPPA
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000005 A        0000 R 000010 ALPHA    0000 R 000002 A1      0003 R 000000 BETA     0000 R 000003 B1
    0000 R 000004 C        0004 R 000000 CAPPA    0000 R 000000 CPF     0000 R 000011 CV       0000   000024 INJP$
    0000 R 000001 R        0000 R 000006 RHOX     0000 R 000007 TX      0000 R 000012 X1


00101            FUNCTION CPF(RHO,T)
00101        C
00101        C      THIS FUNCTION SUBPROGRAM COMPUTES :
00101        C      SPECIFIC HEAT AT CONSTANT PRESSURE AS A FUNCTION OF
00101        C           DENSITY (SLUG/CU.FT) AND TEMPERATURE (R) OF HELIUM
00101        C                                UNITS BTU/(SLUG.R)
00101        C
00103            DATA R,A1,B1,C,A /2077.02,136.9595,3.5002295E-03,10.000658,1.49610
00103           13E-02/
00111            RHOX  = RHO*515.4275
00112            TX    = T/1.8
00113            ALPHA = C*RHOX/(TX**3)
00114            CV    = R*(1.5+6.0*ALPHA*(1.0+RHOX*B1*0.5))
00115            X1    = BETA(RHO,T)*1.8
00116            CPF   = (CV+(TX*X1*X1*47.872)/(RHOX*CAPPA(RHO,T)))*76.8624E-04
00117            RETURN
00120            END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  CPF/CFNAK  ******
```

```
@FOR,S ME*NASA5.CPF/CFNAK,ME*NASA5.CPF/CFNAK
FOR S9A-07/13/72-20:54:47 (0,)

   FUNCTION CPF          ENTRY POINT 000071

   STORAGE USED: CODE(1) 000104; DATA(0) 000032; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   CAPPA
    0004   PF
    0005   ALOG
    0006   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0003 R 000000 CAPPA     0000 R 000014 CP       0000 R 000000 CPF      0000 R 000010 C1      0000 R 000011 C2
    0000 R 000007 DT        0000   000023 INJP$    0004 R 000000 PF       0000 R 000012 P0      0000 R 000016 P1
    0000 R 000013 THETA     0000 R 000015 TK       0000 R 000006 T0       0000 R 000001 X1      0000 R 000002 X2
    0000 R 000003 X3        0000 R 000004 X4       0000 R 000005 X5


00101      1*            FUNCTION CPF(RHO,T)
00101      2*      C
00101      3*      C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*      C        SPECIFIC HEAT AT CONSTANT PRESSURE AS A FUNCTION OF
00101      5*      C              DENSITY (SLUG/CU.FT) AND TEMPERATURE (R) OF NAK 78.6
00101      6*      C                                  UNITS BTU/(SLUG.R)
00101      7*      C
00103      8*            DATA X1,X2,X3,X4,X5 /0.2255,-0.016292,0.005396,-0.000758,0.000054/
00103      9*           1,T0,DT /659.67,300.0/,C1,C2 /58.773064,-0.008433/,P0 /2116.224/
00116     10*            THETA = (T-T0)/DT
00117     11*            CP    = (((X5*THETA+X4)*THETA+X3)*THETA+X2)*THETA+X1
00120     12*            TK    = CAPPA(RHO,T)
00121     13*            P1    = PF(RHO,T)-P0
00122     14*            CPF   = (CP-(2.0*T*C2*C2*ALOG(1.0+TK*P1))/(TK*778.26*(C1+C2*T)**3)
00122     15*           1)*32.174
00123     16*            RETURN
00124     17*            END

        END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ****** CPF/CFSIL ******
```

```
@FOR,S ME*NASA5.CPF/CFSIL,ME*NASA5.CPF/CFSIL
FOR S9A-07/13/72-20:54:50 (0,)

   FUNCTION CPF          ENTRY POINT 000350

   STORAGE USED: CODE(1) 000372; DATA(0) 000133; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   PF
    0004   POLY
    0005   NWDU$
    0006   NI02$
    0007   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000    000055 1F       0000 R 000040 A       0000 R 000007 A1      0000 R 000041 A11     0000 R 000010 A2
    0000 R 000042 A22       0000 R 000011 A3      0000 R 000012 A4      0000 R 000013 A5      0000 R 000043 B
    0000 R 000014 B1        0000 R 000044 B11     0000 R 000015 B2      0000 R 000045 B22     0000 R 000016 B3
    0000 R 000017 B4        0000 R 000020 B5      0000 R 000046 C       0000 R 000037 CP      0000 R 000000 CPF
    0000 R 000021 C1        0000 R 000047 C11     0000 R 000022 C2      0000 R 000025 DT      0000 R 000033 DT2
    0000 R 000050 E1        0000 R 000051 E2      0000 R 000052 E3      0000 R 000054 FP      0000    000113 INJP$
    0000 R 000053 P         0003 R 000000 PF      0004 R 000000 POLY    0000 R 000034 THETA   0000 R 000035 THETA1
    0000 R 000036 THETA2    0000 R 000023 T0      0000 R 000024 T01     0000 R 000032 T02     0000 R 000026 X1
    0000 R 000027 X2        0000 R 000030 X3      0000 R 000031 X4      0000 R 000001 Z


 00101            FUNCTION CPF(RHO,T)
 00101      C
 00101      C        THIS FUNCTION SUBPROGRAM COMPUTES :
 00101      C        SPECIFIC HEAT AS A FUNCTION OF DENSITY (SLUG/CU.FT) AND
 00101      C              TEMPERATURE (R) OF DOW CORNING 200 SILICON OIL (1 CS)
 00101      C                                    UNITS BTU/(SLUG.R)
 00101      C              TEMPERATURE .GE. 359.67 AND .LE. 859.67
 00101      C
 00103            DIMENSION Z(6)
 00104            DATA A1,A2,A3,A4,A5 /12.35,2.98333,1.1,-0.48333,0.1/,B1,B2,B3,B4,B
 00104           15 /-1.5,-0.01333,-1.18,0.57333,-0.1/,C1,C2 /0.7767,-0.0288/,T0,T01
 00104           2,DT /559.67,609.67,50.0/,X1,X2,X3,X4 /0.46,0.00471,0.00141,0.00004
 00104           33/,T02,DT2 /539.67,80.0/
 00132            THETA  = (T-T0)/DT
 00133            THETA1 = (T-T01)/DT
 00134            THETA2 = (T-T02)/DT2
 00135            CP   = ((X4*THETA2+X3)*THETA2+X2)*THETA2+X1
 00136            A    = ((((A5*THETA+A4)*THETA+A3)*THETA+A2)*THETA+A1)*1.0E-06
 00137            A11 = (((4.0*A5*THETA+3.0*A4)*THETA+2.0*A3)*THETA+A2)*(1.0E-06)/DT
 00140            A22 = ((12.0*A5*THETA+6.0*A4)*THETA+2.0*A3)*(1.0E-06)/(DT*DT)
 00141            B    = ((((B5*THETA+B4)*THETA+B3)*THETA+B2)*THETA+B1)*1.0E-09
 00142            B11 = (((4.0*B5*THETA+3.0*B4)*THETA+2.0*B3)*THETA+B2)*(1.0E-09)/DT
 00143            B22 = ((12.0*B5*THETA+6.0*B4)*THETA+2.0*B3)*(1.0E-09)/(DT*DT)
```

```
      C   = C1+C2*THETA1
      C11 = C2/DT
      E1  = A11*A11-B22/2.0+B11*C11/C
      E2  = 2.0*A11*C11/C-A22
      E3  = A*A-B
      P   = PF(RHO,T)/144.0-14.696
      Z(1)  = 0.0
      Z(2)  = 2.0*(C11/C)**2
      Z(3)  = (E2-A*Z(2))/2.0
      Z(4)  = (E1-A*E2+E3*Z(2)/2.0)/3.0
      Z(5)  = (A11*B11-A*E1+E3*E2/2.0+A*B*Z(2)/2.0)/4.0
      Z(6)  = (B11*B11/2.0-2.0*A*A11*B11+E1*E3+A*B*E2+B*B*Z(2)/2.0)/10.0
      FP  = POLY(6,Z,P)
      CPF = (CP-T*FP/(C*337.37))*32.174
      IF (T.GE.360.67.AND.T.LE.860.67) RETURN
      WRITE (6,1) T
    1 FORMAT (1H0,54HSPECIFIC HEAT OF SILICON OIL, TEMP. OUT OF RANGE, T
     1 = ,F8.3,/)
      RETURN
      END
```

END OF COMPILATION: NO DIAGNOSTICS.

@HDG,P ****** CPFN/FNAL ******

```
@FOR,S ME*NASA5.CPFN/FNAL,ME*NASA5.CPFN/FNAL
FOR S9A-07/13/72-20:54:54 (0,)

   FUNCTION CPFN        ENTRY POINT 000056

   STORAGE USED: CODE(1) 000062; DATA(0) 000040; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000     000012 1F        0000 R 000011 CP        0000 R 000000 CPFN      0000 R 000007 DT        0000     000032 INJP$
    0000 R 000010 THETA       0000 R 000006 T0        0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3
    0000 R 000004 X4          0000 R 000005 X5


00101      1*            FUNCTION CPFN(T)
00101      2*      C
00101      3*      C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*      C        SPECIFIC HEAT AS A FUNCTION OF TEMPERATURE (R) OF ALUMINUM 7075
00101      5*      C                                      UNITS BTU/(SLUG.R)
00101      6*      C             TEMP. GE. 300.0.AND.LE. 1200.0 R
00101      7*      C
00103      8*            DATA X1,X2,X3,X4,X5 /0.182,0.03616,-0.011417,0.00233,-0.000083/,T0
00103      9*           1,DT /400.0,200.0/
00113     10*            THETA = (T-T0)/DT
00114     11*            CP = (((X5*THETA+X4)*THETA+X3)*THETA+X2)*THETA+X1
00115     12*            CPFN = CP*32.174
00116     13*            IF (T.GE.300.0.AND.T.LE.1200.0) RETURN
00120     14*            WRITE (6,1) T
00123     15*          1 FORMAT (1H0,51HSPECIFIC HEAT OF ALUMINUM, TEMP. OUT OF RANGE, T =
00123     16*           1,F8.3,/)
00124     17*            RETURN
00125     18*            END

       END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  CPFN/FNBR  ******
```

```
******  CPFN/FNBR  ******                                                          DATE 071372        PAGE      1

@FOR,S ME*NASA5.CPFN/FNBR,ME*NASA5.CPFN/FNBR
FOR S9A-07/13/72-20:54:57 (0,)

   FUNCTION CPFN        ENTRY POINT 000054

   STORAGE USED: CODE(1) 000060; DATA(0) 000037; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000011 1F        0000 R 000010 CP        0000 R 000000 CPFN      0000 R 000006 DT        0000   000031 INJP$
    0000 R 000007 THETA     0000 R 000005 T0        0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3
    0000 R 000004 X4


00101       C           FUNCTION CPFN(T)
00101       C
00101       C              THIS FUNCTION SUBPROGRAM COMPUTES :
00101       C              SPECIFIC HEAT AS A FUNCTION OF TEMPERATURE (R) OF BERYLIUM WITH
00101       C                   0.84-1.68 BEO
00101       C                                             UNITS BTU/(SLUG.R)
00101       C                   TEMP. GE. 400.0 AND LE. 1700.0 R
00101       C
00103                   DATA X1,X2,X3,X4 /0.536,0.05667,-0.0085,0.00083/,T0,DT /800.,200./
00112                   THETA = (T-T0)/DT
00113                   CP = ((X4*THETA+X3)*THETA+X2)*THETA+X1
00114                   CPFN = CP*32.174
00115                   IF (T.GE.400.0.AND.T.LE.1700.0) RETURN
00117                   WRITE (6,1) T
00122                 1 FORMAT (1H0,51HSPECIFIC HEAT OF BERYLIUM= TEMP. OUT OF RANGE, T =
00122                  1,F8.3,/)
00123                   RETURN
00124                   END

        END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  CPFN/FNCU  ******
```

```
@FOR,S ME*NASA5.CPFN/FNCU,ME*NASA5.CPFN/FNCU
FOR S9A-07/13/72-20:54:59 (0,)

   FUNCTION CPFN        ENTRY POINT 000045

   STORAGE USED: CODE(1) 000051; DATA(0) 000031; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000004 1F        0000 R 000003 CP        0000 R 000000 CPFN       0000   000023 INJP$     0000 R 000001 X1
    0000 R 000002 X2


00101      1*           FUNCTION CPFN(T)
00101      2*     C
00101      3*     C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*     C        SPECIFIC HEAT AS A FUNCTION OF TEMPERATURE (R) OF COPPER
00101      5*     C                                    UNITS BTU/(SLUG.R)
00101      6*     C             TEMP. GE. 400.0 AND LE. 1800.0 R
00101      7*     C
00103      8*           DATA X1,X2 /0.08375,1.375E-05/
00106      9*           CP = X2*T+X1
00107     10*           CPFN = CP*32.174
00110     11*           IF (T.GE.400.0.AND.T.LE.1800.0) RETURN
00112     12*           WRITE (6,1) T
00115     13*         1 FORMAT (1H0,49HSPECIFIC HEAT OF COPPER, TEMP. OUT OF RANGE, T = ,
00115     14*          1F8.3,/)
00116     15*           RETURN
00117     16*           END

       END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  CPMP/MPAL  ******
```

```
@FOR,S ME*NASA5.CPMP/MPAL,ME*NASA5.CPMP/MPAL
FOR S9A-07/13/72-20:55:01 (0,)

   FUNCTION CPMP        ENTRY POINT 000056

   STORAGE USED: CODE(1) 000062; DATA(0) 000040; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003    NWDU$
    0004    NIO2$
    0005    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000    000012 1F         0000 R 000011 CP         0000 R 000000 CPMP        0000 R 000007 DT          0000    000032 INJP$
    0000 R 000010 THETA       0000 R 000006 T0         0000 R 000001 X1          0000 R 000002 X2          0000 R 000003 X3

            R                          R
    0000    00000   X         0000    00000   X
                 4   4                     5   5


00101              FUNCTION CPMP(T)
00101        C
00101        C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101        C        SPECIFIC HEAT AS A FUNCTION OF TEMPERATURE (R) OF ALUMINUM 7075
00101        C                                       UNITS BTU/(SLUG.R)
00101        C               TEMP. GE. 300.0.AND.LE. 1200.0 R
00101        C
00103              DATA X1,X2,X3,X4,X5 /0.182,0.03616,-0.011417,0.00233,-0.000083/,T0
00103             1,DT /400.0,200.0/
00113              THETA = (T-T0)/DT
00114              CP = (((X5*THETA+X4)*THETA+X3)*THETA+X2)*THETA+X1
00115              CPMP = CP*32.174
00116              IF (T.GE.300.0.AND.T.LE.1200.0) RETURN
00120              WRITE (6,1) T
00123            1 FORMAT (1H0,51HSPECIFIC HEAT OF ALUMINUM, TEMP. OUT OF RANGE, T =
00123             1,F8.3,/)
00124              RETURN
00125              END

        END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  CPMP/MPBR  ******
```

```
@FOR,S ME*NASA5.CPMP/MPBR,ME*NASA5.CPMP/MPBR
FOR S9A-07/13/72-20:55:03 (0,)

   FUNCTION CPMP        ENTRY POINT 000054

   STORAGE USED: CODE(1) 000060; DATA(0) 000037; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000011 1F       0000 R 000010 CP       0000 R 000000 CPMP     0000 R 000006 DT       0000   000031 INJP$
    0000 R 000007 THETA    0000 R 000005 TO       0000 R 000001 X1       0000 R 000002 X2       0000 R 000003 X3
    0000 R 000004 X4


00101      1*            FUNCTION CPMP(T)
00101      2*      C
00101      3*      C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*      C        SPECIFIC HEAT AS A FUNCTION OF TEMPERATURE (R) OF BERYLIUM WITH
00101      5*      C             0.84-1.68 BEO
00101      6*      C                                     UNITS BTU/(SLUG.R)
00101      7*      C             TEMP. GE. 400.0 AND LE. 1700.0 R
00101      8*      C
00103      9*            DATA X1,X2,X3,X4 /0.536,0.05667,-0.0085,0.00083/,TO,DT /800.,200./
00112     10*            THETA = (T-TO)/DT
00113     11*            CP = ((X4*THETA+X3)*THETA+X2)*THETA+X1
00114     12*            CPMP = CP*32.174
00115     13*            IF (T.GE.400.0.AND.T.LE.1700.0) RETURN
00117     14*            WRITE (6,1) T
00122     15*          1 FORMAT (1H0,51HSPECIFIC HEAT OF BERYLIUM= TEMP. OUT OF RANGE, T =
00122     16*           1,F8.3,/)
00123     17*            RETURN
00124     18*            END

        END OF COMPILATION:          NO  DIAGNOSTICS.


@HDG,P  ****** CPMP/MPCU ******
```

```
****** CPMP/MPCU ******                                                                    DATE 071372        PAGE      1

@FOR,S ME*NASA5.CPMP/MPCU,ME*NASA5.CPMP/MPCU
FOR S9A-07/13/72-20:55:06 (0,)

   FUNCTION CPMP        ENTRY POINT 000045

   STORAGE USED: CODE(1) 000051; DATA(0) 000031; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003    NWDU$
    0004    NI02$
    0005    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000    000004 1F        0000 R 000003 CP        0000 R 000000 CPMP      0000   000023 INJP$     0000 R 000001 X1
    0000 R 000002 X2


 00101      1*           FUNCTION CPMP(T)
 00101      2*      C
 00101      3*      C       THIS FUNCTION SUBPROGRAM COMPUTES :
 00101      4*      C       SPECIFIC HEAT AS A FUNCTION OF TEMPERATURE (R) OF COPPER
 00101      5*      C                                  UNITS BTU/(SLUG.R)
 00101      6*      C            TEMP. GE. 400.0 AND LE. 1800.0 R
 00101      7*      C
 00103      8*           DATA X1,X2 /0.08375,1.375E-05/
 00106      9*           CP = X2*T+X1
 00107     10*           CPMP = CP*32.174
 00110     11*           IF (T.GE.400.0.AND.T.LE.1800.0) RETURN
 00112     12*           WRITE (6,1) T
 00115     13*         1 FORMAT (1H0,49HSPECIFIC HEAT OF COPPER, TEMP. OUT OF RANGE, T = ,
 00115     14*          1F8.3,/)
 00116     15*           RETURN
 00117     16*           END

      END OF COMPILATION:        NO  DIAGNOSTICS.


 @HDG,P  ******  CPTB/TBAL  ******
```

```
@FOR,S ME*NASA5.CPTB/TBAL,ME*NASA5.CPTB/TBAL
FOR S9A-07/13/72-20:55:08 (0,)

   FUNCTION CPTB        ENTRY POINT 000056

   STORAGE USED: CODE(1) 000062; DATA(0) 000040; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NIO2$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000012 1F       0000 R 000011 CP      0000 R 000000 CPTB    0000 R 000007 DT      0000   000032 INJP$
    0000 R 000010 THETA    0000 R 000006 T0      0000 R 000001 X1      0000 R 000002 X2      0000 R 000003 X3
    0000 R 000004 X4       0000 R 000005 X5


 00101            FUNCTION CPTB(T)
 00101      C
 00101      C        THIS FUNCTION SUBPROGRAM COMPUTES :
 00101      C        SPECIFIC HEAT AS A FUNCTION OF TEMPERATURE (R) OF ALUMINUM 7075
 00101      C                                  UNITS BTU/(SLUG,R)
 00101      C            TEMP. GE. 300.0.AND.LE. 1200.0 R
 00101      C
 00103            DATA X1,X2,X3,X4,X5 /0.182,0.03616,-0.011417,0.00233,-0.000083/,T0
 00103           1,DT /400.0,200.0/
 00113            THETA = (T-T0)/DT
 00114            CP = (((X5*THETA+X4)*THETA+X3)*THETA+X2)*THETA+X1
 00115            CPTB = CP*32.174
 00116            IF (T.GE.300.0.AND.T.LE.1200.0) RETURN
 00120            WRITE (6,1) T
 00123          1 FORMAT (1H0,51HSPECIFIC HEAT OF ALUMINUM, TEMP. OUT OF RANGE, T =
 00123           1,F8.3,/)
 00124            RETURN
 00125            END

      END OF COMPILATION:       NO  DIAGNOSTICS.


 @HDG,P  ******  CPTB/TBBR  ******
```

```
****** CPTB/TBBR ******                                                              DATE 071372        PAGE     1

@FOR,S ME*NASA5.CPTB/TBBR,ME*NASA5.CPTB/TBBR
FOR S9A-07/13/72-20:55:10 (0,)

   FUNCTION CPTB        ENTRY POINT 000054

   STORAGE USED: CODE(1) 000060; DATA(0) 000037; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000011 1F        0000 R 000010 CP        0000 R 000000 CPTB      0000 R 000006 DT        0000   000031 INJP$
    0000 R 000007 THETA     0000 R 000005 T0        0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3
    0000 R 000004 X4


00101           FUNCTION CPTB(T)
00101     C
00101     C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101     C        SPECIFIC HEAT AS A FUNCTION OF TEMPERATURE (R) OF BERYLIUM WITH
00101     C              0.84-1.68 BEO
00101     C                                           UNITS BTU/(SLUG.R)
00101     C              TEMP. GE. 400.0 AND LE. 1700.0 R
00101     C
00103           DATA X1,X2,X3,X4 /0.536,0.05667,-0.0085,0.00083/,T0,DT /800.,200./
00112           THETA = (T-T0)/DT
00113           CP = ((X4*THETA+X3)*THETA+X2)*THETA+X1
00114           CPTB = CP*32.174
00115           IF (T.GE.400.0.AND.T.LE.1700.0) RETURN
00117           WRITE (6,1) T
00122         1 FORMAT (1H0,51HSPECIFIC HEAT OF BERYLIUM= TEMP. OUT OF RANGE, T =
00122          1,F8.3,/)
00123           RETURN
00124           END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  CPTB/TBCU  ******
```

```
@FOR,S ME*NASA5.CPTB/TBCU,ME*NASA5.CPTB/TBCU
FOR S9A-07/13/72-20:55:13 (0,)

   FUNCTION CPTB        ENTRY POINT 000045

   STORAGE USED: CODE(1) 000051; DATA(0) 000031; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000004 1F        0000 R 000003 CP        0000 R 000000 CPTB      0000   000023 INJP$     0000 R 000001 X1
    0000 R 000002 X2


00101      1*           FUNCTION CPTB(T)
00101      2*     C
00101      3*     C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*     C        SPECIFIC HEAT AS A FUNCTION OF TEMPERATURE (R) OF COPPER
00101      5*     C                                    UNITS BTU/(SLUG.R)
00101      6*     C             TEMP. GE. 400.0 AND LE. 1800.0 R
00101      7*     C
00103      8*           DATA X1,X2 /0.08375,1.375E-05/
00106      9*           CP = X2*T+X1
00107     10*           CPTB = CP*32.174
00110     11*           IF (T.GE.400.0.AND.T.LE.1800.0) RETURN
00112     12*           WRITE (6,1) T
00115     13*         1 FORMAT (1H0,49HSPECIFIC HEAT OF COPPER, TEMP. OUT OF RANGE, T = ,
00115     14*          1F8.3,/)
00116     15*           RETURN
00117     16*           END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  DDX  ******
```

```
****** DDX ******                                                                    DATE 071372        PAGE      1

@FOR,S ME*NASA5.DDX,ME*NASA5.DDX
FOR S9A-07/13/72-20:55:15 (0,)

   SUBROUTINE DDX        ENTRY POINT 000127

   STORAGE USED: CODE(1) 000153; DATA(0) 000046; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000061 112G      0001   000102 2L        0000   000003 3F        0000 R 000000 DX1       0000 I 000002 I
    0000   000016 INJP$     0000 I 000001 N1



00101             SUBROUTINE DDX (Y,DY,DX,N)                                        1
00101       C
00101       C   THIS SUBROUTINE.COMPUTES :
00101       C     THE FIRST DERIVATIVE OF THE EQUALLY-SPACED ARRAY Y(N)
00101       C
00103             DIMENSION Y(N),DY(N)                                              2
00104             IF (N.LT.3) GO TO 2
00106             DX1 = 2.0*DX                                                      5
00107             DY(1) = (-3.0*Y(1)+4.0*Y(2)-Y(3))/DX1
00110             N1 = N-1                                                          6
00111             DO 1 I=2,N1                                                       7
00114           1 DY(I) = (Y(I+1)-Y(I-1))/DX1                                       8
00116             DY(N) = (Y(N-2)-4.0*Y(N-1)+3.0*Y(N))/DX1
00117             RETURN                                                            10
00120           2 WRITE (6,3)                                                       11
00122           3 FORMAT (25HDDX NOT ENOUGH NODAL PTS../)                           12
00123             RETURN                                                            13
00124             END                                                               14

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P ****** DEFINT ******
```

```
@FOR,S ME*NASA5.DEFINT,ME*NASA5.DEFINT
FOR S9A-07/13/72-20:55:18 (0,)

   FUNCTION DEFINT      ENTRY POINT 000203

   STORAGE USED: CODE(1) 000225; DATA(0) 000046; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000166 10L      0001   000117 131G     0001   000126 136G     0001   000032 2L       0001   000054 4L
    0000 R 000000 DEFINT   0000   000024 INJP$    0000 I 000011 K        0000 I 000005 M        0000 I 000006 NC
    0000 I 000010 NEVE     0000 I 000007 NODD     0000 I 000003 N1       0000 I 000004 N2       0000 R 000001 SEVE
    0000 R 000002 SODD


 00101           FUNCTION DEFINT(Y,DX,N)
 00101       C
 00101       C  THIS FUNCTION SUBPROGRAM COMPUTES :
 00101       C    THE DEFINITE INTEGRAL BY SIMPSONS RULE OF THE EQUALLY-SPACED
 00101       C    ARRAY Y(N)
 00101       C
 00103           DIMENSION Y(N)
 00104           IF(N-3)10,1,2
 00107         1 DEFINT = (DX/3.)*(Y(1)+4.*Y(2)+Y(3))
 00110           RETURN
 00111         2 IF(N-4)10,3,4
 00114         3 DEFINT = (3.*DX/8.)*(Y(1)+3.*(Y(2)+Y(3))+Y(4))
 00115           RETURN
 00116         4 SEVE = 0.
 00117           SODD = 0.
 00120           N1 = N/2
 00121           N2 = 2*N1
 00122           M  = N
 00123           NC = M-N2
 00124           IF(NC.EQ.0) M=N-1
 00126           NODD = M-1
 00127           NEVE = M-2
 00130           DO 7 K=2,NODD,2
 00133         7 SODD = SODD+Y(K)
 00135           DO 8 K=3,NEVE,2
 00140         8 SEVE = SEVE+Y(K)
 00142           DEFINT=(DX/3.)*(Y(1)+Y(M)+4.*SODD+2.*SEVE)
 00143           IF(NC)10,9,10
 00146         9 DEFINT = DEFINT+(DX/24.)*(9.*Y(N)+19.*Y(N-1)-5.*Y(N-2)+Y(N-3))
 00147        10 RETURN
 00150           END
```

****** DEFINT ****** DATE 071372 PAGE 2

END OF COMPILATION: NO DIAGNOSTICS.

@HDG,P ****** DEFNT ******

```
@FOR,S ME*NASAS.DEFNT,ME*NASAS.DEFNT
FOR S9A-07/13/72-20:55:22 (0,)

   FUNCTION DEFNT       ENTRY POINT 000046

   STORAGE USED: CODE(1) 000060; DATA(0) 000023; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000020 107G      0000 R 000000 DEFNT     0000 I 000003 I         0000   000007 INJP$     0000 I 000001 L1
    0000 R 000002 Z


00101         C      FUNCTION DEFNT(Y,DX,N)
00101         C
00101         C   THIS SUBROUTINE COMPUTES :
00101         C     THE DEFINITE INTEGRAL BY TRAPEZOIDAL RULE OF THE EQUALLY-SPACED
00101         C     ARRAY Y(N)
00101         C
00103                DIMENSION Y(N)
00104                L1    = N-1
00105                Z     = 0.0
00106                DO 5 I= 2,L1
00111              5 Z     = Z+Y(I)
00113                DEFNT = DX*(Y(1)+2.0*Z+Y(N))/2.0
00114                RETURN
00115                END

       END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  DERIVL  ******
```

```
@FOR,S ME*NASA5.DERIVL,ME*NASA5.DERIVL
FOR S9A-07/13/72-20:55:25 (0,)

   SUBROUTINE DERIVL    ENTRY POINT 000245

   STORAGE USED: CODE(1) 000257; DATA(0) 000053; BLANK COMMON(2) 001115

    COMMON BLOCKS:

    0003   FLCMP  000024

   EXTERNAL REFERENCES (BLOCK, NAME)

    0004   RHOF
    0005   CAPPA
    0006   BETA
    0007   CPF
    0010   NERR2$
    0011   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000177 10L      0001   000132 5L       0002   000562 AUX2     0000 R 000012 A11     0000 R 000013 A13
    0000 R 000017 A21      0000 R 000020 A23      0000 R 000014 A31      0000 R 000015 A32     0000 R 000016 A33
    0006 R 000000 BETA     0000 R 000021 B1       0000 R 000022 B2       0005 R 000000 CAPPA   0002   000752 COB
    0002   001107 COH      0002   000574 CONFN    0002   000740 CONMP    0007 R 000000 CPF     0002 R 001070 CP0
    0000 R 000023 C1       0000 R 000024 C2       0000 R 000025 C3       0002   001072 DELTA   0002   000764 DOB
    0003 R 000000 DTHETA   0002   001110 DXI      0002   001053 DXIMP    0002   001052 DXITB   0002   001051 DZ
    0002   001103 FENTH    0002   001045 FF0      0002   001101 FLUX     0002 R 001041 FMACH   0002 R 001040 FNU
    0002   001046 FOF      0002   000012 FP       0002 R 001042 FPR      0002 R 001037 FR      0002   001050 FRAD
    0002   001111 FRD      0002   001036 FRE      0002   001104 FREJ     0002   001043 FRL     0002   001044 FRM
    0002 R 000036 FT       0002   000024 FW       0002   001113 FXHW     0002   001112 FXOH    0002 R 001047 FZ
    0000 R 000010 GBETA    0000 R 000011 GCP      0000 R 000007 GKAPPA   0002   001105 HFN     0002 I 001003 IFLOW
    0000   000030 INJP$    0002   001024 LC       0002   001032 LIM      0002   001031 LIMWRT  0002   001011 LL1
    0002   001012 LL2      0002   001013 LL3      0002   001014 LL4      0002   001015 LL5     0002   001016 LL6
    0002   001017 LL7      0002   001006 LMP      0002   001004 LT       0002   001005 LTB     0002   001007 LTBMZ
    0002   001010 LTB2MZ   0002   001030 MM1      0002   001033 MOD      0002   001025 MSTOTR  0002   000777 MZ
    0002   001034 NCCZ     0002   001035 NCONV    0002 I 001002 NCTL     0002   001026 NCTM    0002   001023 NEQUS
    0002   001027 NM1      0002   001001 NRMP     0002   001020 NRMP1    0002   001022 NRMP2   0002   001000 NRTB
    0002   001021 NRTB1    0002   000776 NX       0000 R 000000 P        0002   001063 PHIF    0002   001062 PHIM
    0002   001071 PI       0000 R 000003 PP       0002 R 001065 P0       0002   001102 QREF    0002   000360 QRFN
    0002   000524 QRMP     0002   001074 RDTWRT   0000 R 000006 RHO      0004 R 000000 RHOF    0002   001114 RHOFN
    0002 R 001067 RHOO     0002   001073 RLIMIT   0000 R 000005 RRHO     0002   001100 RTEND   0000 R 000002 T
    0002   000132 TEMP     0002   001077 TI       0002   001076 TINTL    0002   000276 TMP     0002   001075 TREF
    0000 R 000004 TT       0002 R 000050 TW       0002 R 001064 T0       0000 R 000001 W       0002   001066 W0
    0002   000536 XIFN     0002   000005 XIMP     0002   000000 XITB     0002   001106 XL      0002   001054 XRE
    0002   001057 XX10     0002   001060 XX11     0002   001061 XX12     0002   001055 XX3     0002   001056 XX4
    0002   000550 ZETA


 00101      1*         SUBROUTINE DERIVL (Y,DY,X)
```

```
00101      C
00101      C    THIS SUBROUTINE COMPUTES :
00101      C      SPATIAL DERIVATIVES DY OF Y
00101      C
00103           COMMON XITB(5),XIMP(5),FP(10),FW(10),FT(10),TW(10,5),TEMP(10,10),
00103          1        TMP(10,5),QRFN(10,10),QRMP(10),XIFN(10),ZETA(10),AUX2(10),
00103          2        CONFN(10,10),CONMP(10),COB(10),DOB(10)
00104           COMMON NX,MZ,NRTB,NRMP,NCTL,IFLOW,LT,LTB,LMP,LTBMZ,LTB2MZ,LL1,
00104          1       LL2,LL3,LL4,LL5,LL6,LL7,NRMP1,NRTB1,NRMP2,NEQUS,LC,MSTOTR,
00104          2       NCTM,NM1,MM1,LIMWRT,LIM,MOD,NCCZ,NCONV
00105           COMMON FRE,FR,FNU,FMACH,FPR,FRL,FRM,FF0,FOF,FZ,FRAD,DZ,DXITB,DXIMP
00105          1        ,XRE,XX3,XX4,XX10,XX11,XX12,PHIM,PHIF,T0,P0,W0,RHO0,CP0,PI
00105          2        ,DELTA,RLIMIT,RDTWRT,TREF,TINTL,TI,RTEND,FLUX,QREF,FENTH,
00105          3        FREJ,HFN,XL,COH,DXI,FRD,FXOH,FXHW,RHOFN
00106           COMMON/FLCMP/DTHETA(20)
00106      C
00107           DIMENSION Y(3),DY(3)
00107      C
00110           P    = Y(1)
00111           W    = Y(2)                                                07
00112           T    = Y(3)                                                08
00113           IF (IFLOW .EQ. 2) T = FT(NCTL)
00113      C
00115           PP     = P0*P
00116           TT     = T0*T
00117           RRHO   = RHOF(PP,TT)
00120           RHO    = RRHO/RHO0
00121           GKAPPA = CAPPA(RRHO,TT)*P0
00122           GBETA  = BETA(RRHO,TT)*T0
00123           GCP    = CPF(RRHO,TT)/CP0
00123      C                                                               010
00124           A11 = FPR                                                  011
00125           A13 = W*RHO                                                012
00126           A31 = GKAPPA
00127           A32 = -GBETA
00130           A33 = 1.0/W
00131           A21 = FZ*(1.0+T*A32)/(RHO*GCP)
00132           A23 = W*FMACH/GCP
00132      C                                                               017
00133           B1  = (-FR*RHO*W**2)/2.0                                   01
00134           B2  = FNU*(TW(NCTL,1)-T)                                   019
00135           GO TO (5,10), IFLOW
00135      C                                                               020
00136         5 C1  = A21*A32-A31
00137           C2  = A23*A32-A33
00140           C3  = A11*C2-A13*C1                                        023
00140      C
00141           DY(1) = (B1*C2-A13*A32*B2)/C3
00142           DY(2) = (A11*A32*B2-B1*C1)/C3
00143           DY(3) = -(A31*DY(1)+A33*DY(2))/A32
00144           RETURN
00144      C                                                               028
00144      C
00145        10 C1    = DTHETA(NCTL)*A32
00146           C2    = A11*A33-A13*A31
00146      C
00147           DY(1) = (A13*C1+A33*B1)/C2
```

```
00150     59*          DY(2) = -(A11*C1+A31*B1)/C2
00151     60*          RETURN
00152     61*          END

      END OF COMPILATION:      · NO  DIAGNOSTICS.


@HDG,P  ******  DERIVM  ******
```

```
@FOR,S ME*NASA5.DERIVM,ME*NASA5.DERIVM
FOR S9A-07/13/72-20:55:28 (0,)

 SUBROUTINE DERIVM     ENTRY POINT 002331

 STORAGE USED: CODE(1) 002360; DATA(0) 001061; BLANK COMMON(2) 001115

  COMMON BLOCKS:

  0003   DVM     000002
  0004   QIN     001610
  0005   FLDINL  000457
  0006   DVCMFL  000002

 EXTERNAL REFERENCES (BLOCK, NAME)

  0007   CONVEC
  0010   QRAD
  0011   DDX
  0012   D2DX2
  0013   THCFN
  0014   DTHCFN
  0015   CPFN
  0016   YINT
  0017   RHOF
  0020   VISC
  0021   THCF
  0022   CPF
  0023   FLSTRT
  0024   CAPPA
  0025   BETA
  0026   THCTB
  0027   CPTB
  0030   DTHCTB
  0031   THCMP
  0032   CPMP
  0033   DTHCMP
  0034   EXP
  0035   NERR3$

 STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

  0001    000041 114G    0001    000047 121G    0001    000061 125G    0001    000173 130L    0001    000075 133G
  0001    000220 140L    0001    000111 142G    0001    000124 146G    0001    000141 154G    0001    000146 160G
  0001    000204 170G    0001    000243 205G    0001    000263 210G    0001    000310 217G    0001    000323 226G
  0001    000341 231G    0001    000366 240G    0001    000401 247G    0001    000420 253G    0001    000536 271G
  0001    000575 277G    0001    000772 336G    0001    001121 366G    0001    001137 371G    0001    001154 377G
  0001    001174 405G    0001    001211 414G    0001    001235 420G    0001    001272 431G    0001    001361 443G
  0001    001377 446G    0001    001414 454G    0001    001434 462G    0001    001451 471G    0001    001475 475G
  0001    000633 502L    0001    001534 506G    0001    000760 506L    0001    001055 510L    0001    001056 515L
  0001    001731 527G    0001    001755 537G    0001    002116 555G    0001    002262 605G    0001    002112 900L
  0001    002177 901L    0001    002215 902L    0001    002221 903L    0002 R  000562 AUX2    0025 R  000000 BETA
  0024 R  000000 CAPPA   0000 R  000722 CCP     0002 R  000752 COB     0002    001107 COH     0000 R  000676 CON
```

```
0000 R 000702 COND      0002 R 000574 CONFN     0002 R 000740 CONMP     0000 R 000701 CPARM     0022 R 000000 CPF
0015 R 000000 CPFN      0032 R 000000 CPMP      0027 R 000000 CPTB      0002 R 001070 CP0       0000 R 000677 DCON
0002 R 001072 DELTA     0000 R 000700 DIFF      0002 R 000764 DOB       0000 R 000024 DP        0000 R 000012 DTF
0014 R 000000 DTHCFN    0033 R 000000 DTHCMP    0030 R 000000 DTHCTB    0000 R 000036 DW        0002 R 001110 DXI
0002 R 001053 DXIMP     0002 R 001052 DXITB     0000 R 000050 DXTW      0002 R 001051 DZ        0000 R 000214 DZTW
0000 R 000000 D2TF      0000 R 000360 D2XTW     0000 R 000524 D2ZTW     0002   001103 FENTH     0002 R 001045 FFO
0005 R 000456 FLDINT    0002   001101 FLUX      0006 R 000001 FLUXI     0002 R 001041 FMACH     0002 R 001040 FNU
0002 R 001046 FOF       0002 R 000012 FP        0002   001042 FPR       0002 R 001037 FR        0002 R 001050 FRAD
0002 R 001111 FRD       0002   001036 FRE       0002   001104 FREJ      0002   001043 FRL       0002   001044 FRM
0002 R 000036 FT        0002 R 000024 FW        0002 R 001113 FXHW      0002 R 001112 FXOH      0002 R 001047 FZ
0000 R 000724 GBETA     0000 R 000725 GCP       0000 R 000733 GDTHC     0000 R 000734 GFNU      0000 R 000732 GFO
0000 R 000723 GKAPPA    0002   001105 HFN       0000 I 000671 I         0002   001003 IFLOW     0000 I 000674 IM2
0000   001014 INJP$     0000 I 000670 J         0000 I 000672 K         0000 I 000761 KZ        0000 I 000760 K1
0002 I 001024 LC        0005 I 000001 LFLD      0002   001032 LIM       0002   001031 LIMWRT    0000 I 000726 LLT
0002 I 001011 LL1       0002 I 001012 LL2       0002 I 001013 LL3       0002 I 001014 LL4       0002 I 001015 LL5
0002 I 001016 LL6       0002 I 001017 LL7       0002 I 001006 LMP       0002 I 001004 LT        0002 I 001005 LTB
0002 I 001007 LTBMZ     0002 I 001010 LTB2MZ    0002 I 001030 MM1       0002   001033 MOD       0002   001025 MSTOTR
0002 I 000777 MZ        0002   001034 NCCZ      0002 I 001035 NCONV     0002   001002 NCTL      0002   001026 NCTM
0002   001023 NEQUS     0005 I 000000 NFLDTA    0002 I 001027 NM1       0000 I 000703 NM2       0002 I 001001 NRMP
0002 I 001020 NRMP1     0002 I 001022 NRMP2     0002 I 001000 NRTB      0002 I 001021 NRTB1     0004   001605 NSRD
0004   001604 NTM       0002 I 000776 NX        0000 R 000707 PFLC      0002 R 001063 PHIF      0002 R 001062 PHIM
0002   001071 PI        0000 R 000717 PP        0000 R 000714 PRTR      0002 R 001065 P0        0000 R 000756 QFN
0004   000454 QIFN      0004   001274 QITB      0000 R 000757 QMP       0002   001102 QREF      0002 R 000360 QRFN
0002 R 000524 QRMP      0004   000144 QSFN      0004   000764 QSTB      0004   001606 QTO       0002   001074 RDTWRT
0000 R 000713 RETR      0000 R 000720 RHO       0000 R 000710 RHOC      0017 R 000000 RHOF      0002 R 001114 RHOFN
0002 R 001067 RHO0      0002   001073 RLIMIT    0000 R 000721 RRHO      0002   001100 RTEND     0000 R 000673 TABS
0002 R 000132 TEMP      0000 R 000706 TFLC      0000 R 000715 TFLIN     0021 R 000000 THCF      0013 R 000000 THCFN
0031 R 000000 THCMP     0026 R 000000 THCTB     0002   001077 TI        0005 R 000146 TIFLD     0002 R 001076 TINTL
0004   000000 TM        0005 R 000002 TMEFLD    0002 R 000276 TMP       0000 R 000755 TMPGRD    0002 R 001075 TREF
0000 R 000675 TT        0000 R 000731 TTB       0000 R 000750 TTHCMP    0000 R 000736 TTM       0000 R 000747 TTMBAR
0002 R 000050 TW        0004 R 001607 TX        0002 R 001064 T0        0020 R 000000 VISC      0005 R 000312 WIFLD
0000 R 000705 WIFLDT    0006 R 000000 WRAT      0002   001066 W0        0002   000536 XIFN      0002 R 000005 XIMP
0002 R 000000 XITB      0002   001106 XL        0002 R 001054 XRE       0000 R 000737 XT        0000 R 000712 XTHCF
0000 R 000741 XTHCT     0000 R 000704 XTME      0000 R 000711 XVISC     0000 R 000742 XX1       0002 R 001057 XX10
0002 R 001060 XX11      0002 R 001061 XX12      0000 R 000743 XX2       0003 R 000000 XX20      0002 R 001055 XX3
0002 R 001056 XX4       0003 R 000001 XX48      0000 R 000744 XX5       0000 R 000745 XX6       0000 R 000716 X00
0000 R 000753 X01       0000 R 000754 X03       0000 R 000727 X1        0000 R 000730 X2        0000 R 000740 X3
0000 R 000751 X4        0000 R 000752 X5        0016 R 000000 YINT      0000 R 000746 YY1       0000 R 000735 Y1
0002   000550 ZETA
```

```
00101           SUBROUTINE DERIVM(Y,DY,TIME)
00101      C
00101      C  THIS SUBROUTINE COMPUTES :
00101      C    ALL DERIVATIVES OF THE VARIABLE Y WITH RESPECT TO TIME
00101      C
00103           COMMON XITB(5),XIMP(5),FP(10),FW(10),FT(10),TW(10,5),TEMP(10,10),
00103          1        TMP(10,5),QRFN(10,10),QRMP(10),XIFN(10),ZETA(10),AUX2(10),
00103          2        CONFN(10,10),CONMP(10),COB(10),DOB(10)
00104           COMMON NX,MZ,NRTB,NRMP,NCTL,IFLOW,LT,LTB,LMP,LTBMZ,LTB2MZ,LL1,
00104          1       LL2,LL3,LL4,LL5,LL6,LL7,NRMP1,NRTB1,NRMP2,NEQUS,LC,MSTOTR,
00104          2       NCTM,NM1,MM1,LIMWRT,LIM,MOD,NCCZ,NCONV
00105           COMMON FRE,FR,FNU,FMACH,FPR,FRL,FRM,FFO,FOF,FZ,FRAD,DZ,DXITB,DXIMP
00105          1        ,XRE,XX3,XX4,XX10,XX11,XX12,PHIM,PHIF,T0,P0,W0,RHO0,CP0,PI
00105          2        ,DELTA,RLIMIT,RDTWRT,TREF,TINTL,TI,RTEND,FLUX,QREF,FENTH,
```

```
00105          3         FREJ,HFN,XL,COH,DXI,FRD,FXOH,FXHW,RHOFN
00106           COMMON/DVM/XX20,XX48
00107           COMMON /QIN/TM(100), QSFN(100,2), QIFN(100,2), QSTB(100,2),
00107          1        QITB(100,2), NTM, NSRD, QTO, TX
00110           COMMON /FLDINL/ NFLDTA,LFLD,TMEFLD(100),TIFLD(100),WIFLD(100),
00110          1              FLDINT
00111           COMMON /DVCMFL/ WRAT,FLUXI
00111     C
00112           DIMENSION Y(200),DY(200),D2TF(10),DTF(10),DP(10),DW(10),
00112          1        DXTW(10,10),DZTW(10,10),D2XTW(10,10),D2ZTW(10,10)
00112     C
00113           DO 100 J=1,MZ
00116       100 TEMP(J,1)  = Y(LL4+J)
00120           DO 105 I=2,NX
00123           K          = MZ*(I-2)
00124           DO 105 J=1,MZ
00127       105 TEMP(J,I)  = Y(K+J)
00127     C
00132           DO 110 J=1,MZ
00135       110 TMP(J,1)   = Y(LL4+J)
00137           IF(NRTB.EQ.0) GO TO 130
00141           DO 115 I=2,NRMP
00144           K          = LMP+(I-2)*MZ
00145           DO 115 J=1,MZ
00150       115 TMP(J,I)   = Y(K+J)
00153           DO 120 J=1,MZ
00156           TW(J,NRTB) = Y(LL4+J)
00157           DO 120 I=1,NRTB1
00162           K          = LTB+(I-1)*MZ+J
00163       120 TW(J,I)    = Y(K)
00163     C
00166           GO TO 140
00167       130 DO 135 J=1,MZ
00172           K            = LL4+J
00173           TW(J,1)      = Y(K)
00174           TMP(J,NRMP)  = Y(K)
00175       135 TEMP(J,1)    = Y(K)
00175     C
00177       140 TABS    =  TIME*TREF*3600.0
00200           TX      = TABS/60.0
00201           IF(NCONV.GT.0) CALL CONVEC (TABS)
00203           CALL QRAD
00203     C
00203     C
00203     C     FIN
00203     C
00203     C
00204           DO 2 I=2,NM1
00207           DO 1 J=1,MZ
00212         1 DTF(J)  = TEMP(J,I)
00214           CALL DDX   (DTF,DP,DZ,MZ)
00215           CALL D2DX2(DTF, DW,DZ,MZ)
00216           DO 2 J=2,MM1
00221           DZTW(J,I)   = DP(J)
00222         2 D2ZTW(J,I)  = DW(J)
00222     C
00225           DO 4 J=2,MM1
```

```
00230              DO 3 I=1,NX
00233            3 DTF(I)  = TEMP(J,I)
00235              CALL DDX  (DTF,DP,DXI,NX)
00236              CALL D2DX2(DTF,DW,DXI,NX)
00237              DO 4 I=2,NM1
00242              DXTW(J,I)    = DP(I)
00243            4 D2XTW(J,I)   = DW(I)
00243        C
00246              DO 9 I=2,NM1
00251              IM2      = I-2
00252              DO 9 J=2,MM1
00255              K        = IM2*MZ+J
00256              TT       = TO*TEMP(J,I)
00257              CON        = THCFN(TT)
00260              DCON     = DTHCFN(TT)*TO
00261              DIFF       = CON/(RHOFN*CPFN(TT))*FXHW
00262              CPARM    = FRD/CON
00262        C
00263              COND     = D2XTW(J,I)+FXOH*D2ZTW(J,I)-COB(I)*DXTW(J,I)
00263             1           +DCON*(DXTW(J,I)**2+FXOH*DZTW(J,I)**2)
00264            9 DY(K)    = DIFF*(COND-DOB(I)*CPARM*(QRFN(J,I)-CONFN(J,I)))
00264        C
00264        C     TIP OF FIN
00264        C
00267              NM2      = NX-2
00270              DO 11 J=2,MM1
00273              K        = NM2*MZ+J
00274           11 DY(K)    = (18.*DY(K-MZ)-9.*DY(K-2*MZ)+2.*DY(K-3*MZ))/11.
00274        C
00274        C
00274        C
00274        C
00274        C     FLUID FLOW VARIABLES
00274        C
00274        C
00276              DO 500 I=1,MZ
00301          500 FT(I) = Y(I+LT)
00301        C
00303              IF (LFLD .EQ. 1) GO TO 502
00305              XTME  = TIME*TREF
00306              FT(1) = YINT(TMEFLD,TIFLD,NFLDTA,3,XTME)/TO
00307              FLDINT = FT(1)
00310              WIFLDT = YINT(TMEFLD,WIFLD,NFLDTA,3,XTME)
00311              WRAT    = WIFLDT/FLUXI
00311        C
00312          502 TFLC  = FT(LC)*TO
00313              PFLC  = FP(LC)*PO
00314              RHOC  = RHOF(PFLC,TFLC)
00315              XVISC = VISC(RHOC,TFLC)
00316              XTHCF = THCF(RHOC,TFLC)
00317              RETR  = XRE/XVISC
00320              PRTR  = (XVISC*CPF(RHOC,TFLC))/XTHCF
00321              TFLIN = Y(LT+1)
00322              CALL FLSTRT(RETR,PRTR,DELTA)
00323              XOO      = DELTA*RETR*PRTR*XTHCF/4.0
00323        C
00324              CALL DDX(FW,DW,DZ,MZ)
```

```
00325            CALL DDX(FT,DTF,DZ,MZ)
00325      C
00326            DY(LT+1) = 0.0
00327            IF (LFLD .EQ. 2) GO TO 506
00331            IF(TIME.LE.2.5) DY(LT+1) = 7.0*EXP(-7.0*TIME)*(1.0-TINTL)
00333        506 AUX2(1) = FNU*(TW(1,1)-FT(1))
00334            AUX2(1) = -X00*AUX2(1)
00334      C
00335            DO 520 I=2,MZ
00340            PP     = P0*FP(I)
00341            TT     = T0*FT(I)
00342            RHO    = 1.0/FW(I)
00343            RRHO   = RHO0*RHO
00344            CCP    = CPF(RRHO,TT)
00344      C
00345            GKAPPA = CAPPA(RRHO,TT)*P0
00346            GBETA  = BETA(RRHO,TT)*T0
00347            GCP    = CCP/CP0
00350            AUX2(I) = FNU*(TW(I,1)-FT(I))
00351            LLT      = LT+I
00352            IF (GKAPPA .LT. 1.0E-08) GO TO 510
00354            X1       = FZ*GBETA*FT(I)/(GKAPPA*GCP*RHO)
00355            GO TO 515
00356        510 X1       = 0.0
00357        515 X2       = 1.0-X1*GBETA
00360            DY(LLT) = ((AUX2(I)+FMACH*FR*(FW(I)**2)/2.0)/(RHO*GCP)-X1*DW(I))/
00360           1          X2-FW(I)*DTF(I)
00361        520 AUX2(I) = -X00*AUX2(I)
00361      C
00361      C
00361      C     TUBE WALL TEMPERATURE
00361      C
00363            IF(NRTB.EQ.0) GO TO 900
00365            DO 625 J=1,MZ
00370            DO 615 I=1,NRTB
00373        615 DTF(I)  = TW(J,I)
00375            CALL DDX(DTF,D2TF,DXITB,NRTB)
00376            DO 620 I=1,NRTB
00401        620 DP(I)    = XITB(I)*D2TF(I)
00403            CALL DDX(DP,DTF,DXITB,NRTB)
00404            DO 625 I=2,NRTB1
00407            D2XTW(J,I)     = DTF(I)/XITB(I)
00410        625 DXTW(J,I)      = (D2TF(I))**2
00410      C
00413            DO 630 I=2,NRTB1
00416            K         = LTB+(I-1)*MZ
00417            DO 630 J=1,MZ
00422            TTB       = TW(J,I)*T0
00423            GF0       = THCTB(TTB)/CPTB(TTB)*FF0
00424            GDTHC     = T0*DTHCTB(TTB)
00425        630 DY(K+J) = GF0*(D2XTW(J,I)+GDTHC*(DXTW(J,I)))
00430            DO 635 J=1,MZ
00433            TTB       = TW(J,1)*T0
00434            GFNU      = XTHCF*FNU/(4.0*THCTB(TTB))*RETR*PRTR*DELTA*DXITB
00435            Y1        = TW(J,1)-FT(J)
00436            X1        = 4.0*DY(LTBMZ+J)-DY(LTB2MZ+J)
00437            X2        = 3.0+GFNU*(1.0-T0*DTHCTB(TTB)*Y1)
```

```
00440      635 DY(LTB+J) = (X1+GFNU*DY(LT+J))/X2
00440   C
00440   C
00440   C
00440   C     PROTECTION LAYER TEMPERATURE
00440   C
00440   C
00442          DO 730 J=1,MZ
00445          DO 720 I=1,NRMP
00450      720 DTF(I) = TMP(J,I)
00452          CALL DDX(DTF,D2TF,DXIMP,NRMP)
00453          DO 725 I=1,NRMP
00456      725 DP(I)   = XIMP(I)*D2TF(I)
00460          CALL DDX(DP,DTF,DXIMP,NRMP)
00461          DO 730 I=2,NRMP1
00464          D2XTW(J,I)    = DTF(I)/XIMP(I)
00465      730 DXTW(J,I)     = D2TF(I)**2
00465   C
00470          DO 735 I=2,NRMP1
00473          K        = LMP+(I-2)*MZ
00474          DO 735 J=1,MZ
00477          TTM      = TMP(J,I)*T0
00500          GF0      = THCMP(TTM)/CPMP(TTM)*F0F
00501          GDTHC    = T0*DTHCMP(TTM)
00502      735 DY(K+J)  = GF0*(D2XTW(J,I)+GDTHC*(DXTW(J,I)))
00502   C
00502   C
00502   C
00502   C     FIN - TUBE - PROTECTION LAYER INTERFACE
00502   C
00505          DO 740 J=1,MZ
00510          XT      = TW(J,1)*T0
00511          X1      = DTHCTB(XT)
00512          X2      = DTHCMP(XT)
00513          X3      = DTHCFN(XT)
00514          XTHCT   = THCTB(XT)
00515          XX1     = PHIM*THCMP(XT)/XTHCT
00516          XX2     = PHIF*THCFN(XT)/XTHCT
00517          XX5     = (X2-X1)*XX3*(-3.0*TW(J,NRTB)+4.0*TMP(J,2)-TMP(J,3))*T0
00520          XX6     = (X3-X1)*XX4*(-3.0*TW(J,NRTB)+4.0*TEMP(J,2)-TEMP(J,3))*T0
00520   C
00521          YY1     = 4.0*DY(LL1+J)-DY(LL2+J)
00522          YY1     = YY1+XX1*XX3*(4.0*DY(LMP+J)-DY(LL3+J))
00523          YY1     = YY1+XX2*XX4*(4.0*DY(J)-DY(MZ+J))
00524      740 DY(LL4+J) = YY1/(3.0+XX1*(3.0*XX3-XX5)+XX2*(3.0*XX4-XX6))
00524   C
00524   C
00524   C     MANIFOLD-FIN INTERFACE
00524   C
00524   C
00526          DO 750 I=1,NM1
00531          K        = I*MZ-(MZ-1)
00532          DY(K)    = DY(LL4+1)
00533          K        = I*MZ
00534      750 DY(K)    = DY(LL4+MZ)
00534   C
00534   C
```

```
00534          C
00534          C
00534          C      OUTER BOUNDARY OF PROTECTION LAYER
00534          C
00534          C
00536                 DO 810 J=1,MZ
00541                 TTMBAR  = (8.0*TMP(J,NRMP)+5.0*TMP(J,NRMP1)-TMP(J,NRMP2))*T0/12.
00542                 TTHCMP  = THCMP(TTM)
00543                 GFO     = TTHCMP*F0F/CPMP(TTMBAR)
00544                 GDTHC   = T0*DTHCMP(TTM)
00545                 X1      = TMP(J,NRMP)-TMP(J,NRMP1)
00546                 X2      = 1.0-GDTHC*(3.0*TMP(J,NRMP)-4.0*TMP(J,NRMP1)+
00546               1              TMP(J,NRMP2))/4.0
00547                 X4      = FRAD*XX12*(QRMP(J)+CONMP(J))/TTHCMP
00550                 X5      = -X1*XX11*X2-X4
00551             810 DY(LL5+J) = (12.0*X5*GFO-5.0*DY(LL6+J)+DY(LL7+J))/8.0
00551          C
00553                 RETURN
00553          C
00554             900 DO 905 J=1,MZ
00557                 K       = LL4+J
00560                 TT      = Y(K)*T0
00561                 TFLC    = T0*FT(J)
00562                 RHOC    = RHO0/FW(J)
00563                 X01     = XX10*CPTB(TT)+XX11*CPMP(TT)+XX12*CPFN(TT)
00564                 X03     = XX4*THCFN(TT)
00565                 IF(J.NE.1) GO TO 901
00567                 TMPGRD  = (5.0*(TEMP(2,2)-TEMP(2,1))+TEMP(3,1)-TEMP(3,2))/XX48
00570                 GO TO 903
00571             901 IF(J.NE.MZ) GO TO 902
00573                 TMPGRD  = (5.0*(TEMP(MM1,2)-TEMP(MM1,1))+TEMP(LL6,1)
00573               1          -TEMP(LL6,2))/XX48
00574                 GO TO 903
00575             902 TMPGRD  = (TEMP(J,2)-TEMP(J,1))/DXI
00576             903 QFN     = QRFN(J,1)+CONFN(J,1)
00577                 QMP     = QRMP(J)+CONMP(J)
00600             905 DY(K)   = (AUX2(J)-FRAD*(QMP+XX20*QFN)+X03*TMPGRD)/X01
00600          C
00602                 K1      = LL4+1
00603                 KZ      = LL4+MZ
00604                 DO 910 I=1,NM1
00607                 K       = I*MZ
00610                 DY(K)   = DY(KZ)
00611                 K       = K-MZ+1
00612             910 DY(K)   = DY(K1)
00614                 RETURN
00615                 END

        END OF COMPILATION:          NO  DIAGNOSTICS.


QHDG,P   ******  DTHCFN/FNAL   ******
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****** DTHCFN/FNAL ******                                                              DATE 071372        PAGE    1

@FOR,S ME*NASA5.DTHCFN/FNAL,ME*NASA5.DTHCFN/FNAL
FOR S9A-07/13/72-20:55:36 (0,)

   FUNCTION DTHCFN      ENTRY POINT 000033

   STORAGE USED: CODE(1) 000040; DATA(0) 000017; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   THCFN
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000006 DT        0000 R 000011 DTHC      0000 R 000000 DTHCFN    0000   000012 INJP$     0000 R 000010 THC
    0003 R 000000 THCFN     0000 R 000007 THETA     0000 R 000005 T0        0000 R 000001 X1        0000 R 000002 X2
    0000 R 000003 X3        0000 R 000004 X4


00101                FUNCTION DTHCFN (T)
00101          C
00101          C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101          C        (1/K)(DK/DT) AS A FUNCTION OF TEMPERATURE (R) OF ALUMINUM 7075
00101          C                                    UNITS (1/R)
00101          C             TEMP. GE. 300.0.AND.LE. 1200.0 R
00101          C
00103                DATA X1,X2,X3,X4 /13.0665,0.6655,-5.25,1.015/,T0,DT /400.0,200.0/
00112                THETA  = (T-T0)/DT
00113                THC    = THCFN(T)
00114                DTHC   = (((X4*THETA+X3)*THETA+X2)*THETA+X1)/DT
00115                DTHCFN = DTHC/THC
00116                RETURN
00117                END
      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  DTHCFN/FNBR  ******
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****** DTHCFN/FNBR ******                                                                    DATE 071372       PAGE      1

@FOR,S ME*NASA5.DTHCFN/FNBR,ME*NASA5.DTHCFN/FNBR
FOR S9A-07/13/72-20:55:39 (0,)

   FUNCTION DTHCFN      ENTRY POINT 000033

   STORAGE USED: CODE(1) 000040; DATA(0) 000017; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   THCMP
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000006 DT       0000 R 000011 DTHC     0000 R 000000 DTHCFN   0000   000012 INJP$     0000 R 000010 THC
    0003 R 000000 THCMP    0000 R 000007 THETA    0000 R 000005 TO       0000 R 000001 X1         0000 R 000002 X2
    0000 R 000003 X3       0000 R 000004 X4

 00101      1*          FUNCTION DTHCFN(T)
 00101      2*     C
 00101      3*     C       THIS FUNCTION SUBPROGRAM COMPUTES :
 00101      4*     C       (1/K)(DK/DT) AS A FUNCTION OF TEMPERA3URE (R) OF BERYLIUM WITH
 00101      5*     C            0.84-1.68 BEO
 00101      6*     C                                    UNITS (1/R)
 00101      7*     C            TEMP. GE. 400.0 AND LE. 1700.0 R
 00101      8*     C
 00103      9*          DATA X1,X2,X3,X4 /-10.5643,1.65366,-0.60501,0.080668/,TO,DT /400.0
 00103     10*         1,200.0/
 00112     11*          THETA  = (T-TO)/DT
 00113     12*          THC    = THCMP(T)
 00114     13*          DTHC   = (((X4*THETA+X3)*THETA+X2)*THETA+X1)/DT
 00115     14*          DTHCFN = DTHC/THC
 00116     15*          RETURN
 00117     16*          END
        END OF COMPILATION:        NO  DIAGNOSTICS.

@HDG,P  ******  DTHCFN/FNCU  ******
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****** DTHCFN/FNCJ ******                                                                    DATE 071372        PAGE      1

QFOR,S ME*NASA5.DTHCFN/FNCU,ME*NASA5.DTHCFN/FNCU
FOR S9A-07/13/72-20:55:41 (0,)

   FUNCTION DTHCFN      ENTRY POINT 000030

   STORAGE USED: CODE(1) 000035; DATA(0) 000015; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   THCTB
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000004 DT        0000 R 000007 DTHC       0000 R 000000 DTHCFN     0000   000010 INJP$       0000 R 000006 THC
    0003 R 000000 THCTB     0000 R 000005 THETA      0000 R 000003 T0         0000 R 000001 X1          0000 R 000002 X2


00101          FUNCTION DTHCFN(T)
00101     C
00101     C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101     C       (1/K)(DK/DT) AS A FUNCTION OF TEMPERATURE (R) OF COPPER
00101     C                                   UNITS (1/R)
00101     C            TEMP. GE. 500.0 AND LE. 1800.0 R
00101     C
00103          DATA X1,X2 /-2.62067,-0.121/,T0,DT /600.0,200.0/
00110          THETA  = (T-T0)/DT
00111          THC    = THCTB(T)
00112          DTHC   = (X2*THETA*THETA+X1)/DT
00113          DTHCFN = DTHC/THC
00114          RETURN
00115          END
      END OF COMPILATION:        NO  DIAGNOSTICS.


QHDG,P  ******  DTHCMP/MPAL  ******
```

```
@FOR,S ME*NASA5.DTHCMP/MPAL,ME*NASA5.DTHCMP/MPAL
FOR S9A-07/13/72-20:55:44 (0,)

   FUNCTION DTHCMP       ENTRY POINT 000033

   STORAGE USED: CODE(1) 000040; DATA(0) 000017; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   THCFN
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000006 DT       0000 R 000011 DTHC     0000 R 000000 DTHCMP   0000   000012 INJP$    0000 R 000010 THC
    0003 R 000000 THCFN    0000 R 000007 THETA    0000 R 000005 TO       0000 R 000001 X1       0000 R 000002 X2
    0000 R 000003 X3       0000 R 000004 X4


00101      1*          FUNCTION DTHCMP(T)
00101      2*     C
00101      3*     C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*     C       (1/K)(DK/DT) AS A FUNCTION OF TEMPERATURE (R) OF ALUMINUM 7075
00101      5*     C                                 UNITS (1/R)
00101      6*     C          TEMP. GE. 300.0.AND.LE. 1200.0 R
00101      7*     C
00103      8*          DATA X1,X2,X3,X4 /13.0665,0.6655,-5.25,1.015/,TO,DT /400.0,200.0/
00112      9*          THETA  = (T-TO)/DT
00113     10*          THC    = THCFN(T)
00114     11*          DTHC   = (((X4*THETA+X3)*THETA+X2)*THETA+X1)/DT
00115     12*          DTHCMP = DTHC/THC
00116     13*          RETURN
00117     14*          END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  DTHCMP/MPBR  ******
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```
@FOR,S ME*NASA5.DTHCMP/MPBR,ME*NASA5.DTHCMP/MPBR
FOR S9A-07/13/72-20:55:46 (0,)

   FUNCTION DTHCMP      ENTRY POINT 000033

   STORAGE USED: CODE(1) 000040; DATA(0) 000017; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   THCMP
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000006 DT        0000 R 000011 DTHC      0000 R 000000 DTHCMP    0000   000012 INJP$     0000 R 000010 THC
    0003 R 000000 THCMP     0000 R 000007 THETA     0000 R 000005 TO        0000 R 000001 X1        0000 R 000002 X2
    0000 R 000003 X3        0000 R 000004 X4


 00101      1*            FUNCTION DTHCMP (T)
 00101      2*      C
 00101      3*      C        THIS FUNCTION SUBPROGRAM COMPUTES :
 00101      4*      C        (1/K)(DK/DT) AS A FUNCTION OF TEMPERA3URE (R) OF BERYLIUM WITH
 00101      5*      C             0.84-1.68 BEO
 00101      6*      C                                          UNITS (1/R)
 00101      7*      C             TEMP. GE. 400.0 AND LE. 1700.0 R
 00101      8*      C
 00103      9*            DATA X1,X2,X3,X4 /-10.5643,1.65366,-0.60501,0.080668/,TO,DT /400.0
 00103     10*           1,200.0/
 00112     11*            THETA  = (T-TO)/DT
 00113     12*            THC    = THCMP(T)
 00114     13*            DTHC   = (((X4*THETA+X3)*THETA+X2)*THETA+X1)/DT
 00115     14*            DTHCMP = DTHC/THC
 00116     15*            RETURN
 00117     16*            END

      END OF COMPILATION:        NO  DIAGNOSTICS.


 @HDG,P  ******  DTHCMP/MPCU  ******
```

```
****** DTHCMP/MPCU ******                                                    DATE 071372      PAGE     1

@FOR,S ME*NASA5.DTHCMP/MPCU,ME*NASA5.DTHCMP/MPCU
FOR S9A-07/13/72-20:55:50 (0,)

   FUNCTION DTHCMP      ENTRY POINT 000030

   STORAGE USED: CODE(1) 000035; DATA(0) 000015; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   THCTB
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000004 DT       0000 R 000007 DTHC     0000 R 000000 DTHCMP    0000   000010 INJP$     0000 R 000006 THC
    0003 R 000000 THCTB    0000 R 000005 THETA    0000 R 000003 T0        0000 R 000001 X1         0000 R 000002 X2


00101             FUNCTION DTHCMP(T)
00101       C
00101       C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101       C        (1/K)(DK/DT) AS A FUNCTION OF TEMPERATURE (R) OF COPPER
00101       C                                         UNITS (1/R)
00101       C              TEMP. GE. 500.0 AND LE. 1800.0 R
00101       C
00103             DATA X1,X2 /-2.62067,-0.121/,T0,DT /600.0,200.0/
00110             THETA  = (T-T0)/DT
00111             THC    = THCTB(T)
00112             DTHC   = (X2*THETA*THETA+X1)/DT
00113             DTHCMP = DTHC/THC
00114             RETURN
00115             END
      END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  DTHCTB/TBAL  ******
```

```
@FOR,S ME*NASA5.DTHCTB/TBAL,ME*NASA5.DTHCTB/TBAL
FOR S9A-07/13/72-20:55:53 (0,)

   FUNCTION DTHCTB      ENTRY POINT 000033

   STORAGE USED: CODE(1) 000040; DATA(0) 000017; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   THCFN
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000006 DT       0000 R 000011 DTHC      0000 R 000000 DTHCTB    0000   000012 INJP$     0000 R 000010 THC
    0003 R 000000 THCFN    0000 R 000007 THETA     0000 R 000005 T0        0000 R 000001 X1        0000 R 000002 X2
    0000 R 000003 X3       0000 R 000004 X4


00101      1*           FUNCTION DTHCTB(T)
00101      2*     C
00101      3*     C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*     C        (1/K)(DK/DT) AS A FUNCTION OF TEMPERATURE (R) OF ALUMINUM 7075
00101      5*     C                                    UNITS (1/R)
00101      6*     C            TEMP. GE. 300.0.AND.LE. 1200.0 R
00101      7*     C
00103      8*           DATA X1,X2,X3,X4 /13.0665,0.6655,-5.25,1.015/,T0,DT /400.0,200.0/
00112      9*           THETA  = (T-T0)/DT
00113     10*           THC    = THCFN(T)
00114     11*           DTHC   = (((X4*THETA+X3)*THETA+X2)*THETA+X1)/DT
00115     12*           DTHCTB = DTHC/THC
00116     13*           RETURN
00117     14*           END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  DTHCTB/TBBR  ******
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```
@FOR,S ME*NASA5.DTHCTB/TBBR,ME*NASA5.DTHCTB/TBBR
FOR S9A-07/13/72-20:55:56 (0,)

   FUNCTION DTHCTB      ENTRY POINT 000033

   STORAGE USED: CODE(1) 000040; DATA(0) 000017; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   THCMP
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000006 DT       0000 R 000011 DTHC      0000 R 000000 DTHCTB    0000   000012 INJP$     0000 R 000010 THC
    0003 R 000000 THCMP    0000 R 000007 THETA     0000 R 000005 TO        0000 R 000001 X1        0000 R 000002 X2
    0000 R 000003 X3       0000 R 000004 X4


00101           FUNCTION DTHCTB(T)
00101      C
00101      C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101      C       (1/K)(DK/DT) AS A FUNCTION OF TEMPERA3URE (R) OF BERYLIUM WITH
00101      C            0.84-1.68 BEO
00101      C                                      UNITS (1/R)
00101      C            TEMP. GE. 400.0 AND LE. 1700.0 R
00101      C
00103           DATA X1,X2,X3,X4 /-10.5643,1.65366,-0.60501,0.080668/,TO,DT /400.0
00103          1,200.0/
00112           THETA  = (T-TO)/DT
00113           THC    = THCMP(T)
00114           DTHC   = (((X4*THETA+X3)*THETA+X2)*THETA+X1)/DT
00115           DTHCTB = DTHC/THC
00116           RETURN
00117           END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  DTHCTB/TBCU  ******
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```
****** DTHCTB/TBCU ******                                                    DATE 071372        PAGE      1

@FOR,S ME*NASA5.DTHCTB/TBCU,ME*NASA5.DTHCTB/TBCU
FOR 59A-07/13/72-20:55:58 (0,)

   FUNCTION DTHCTB      ENTRY POINT 000030

   STORAGE USED: CODE(1) 000035; DATA(0) 000015; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   THCTB
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000004 DT        0000 R 000007 DTHC      0000 R 000000 DTHCTB    0000   000010 INJP$      0000 R 000006 THC
    0003 R 000000 THCTB     0000 R 000005 THETA     0000 R 000003 T0        0000 R 000001 X1         0000 R 000002 X2


 00101         FUNCTION DTHCTB (T)
 00101    C
 00101    C       THIS FUNCTION SUBPROGRAM COMPUTES :
 00101    C       (1/K)(DK/DT) AS A FUNCTION OF TEMPERATURE (R) OF COPPER
 00101    C                                        UNITS (1/R)
 00101    C            TEMP. GE. 500.0 AND LE. 1800.0 R
 00101    C
 00103         DATA X1,X2 /-2.62067,-0.121/,T0,DT /600.0,200.0/
 00110         THETA  = (T-T0)/DT
 00111         THC    = THCTB(T)
 00112         DTHC   = (X2*THETA*THETA+X1)/DT
 00113         DTHCTB = DTHC/THC
 00114         RETURN
 00115         END
       END OF COMPILATION:        NO  DIAGNOSTICS.


 @HDG,P  ******  D2DX2  ******
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```
****** D2DX2 ******                                                                    DATE 071372        PAGE     1

@FOR,S ME*NASA5.D2DX2,ME*NASA5.D2DX2
FOR S9A-07/13/72-20:56:00 (0,)

   SUBROUTINE D2DX2     ENTRY POINT 000137

   STORAGE USED: CODE(1) 000163; DATA(0) 000046; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NIO2$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000064 112G      0001   000112 2L        0000   000003 3F        0000 R 000000 DX2       0000 I 000002 I
    0000   000016 INJP$     0000 I 000001 N1


 00101      1*          SUBROUTINE D2DX2 (Y,D2Y,DX,N)                                       1
 00101      2*     C
 00101      3*     C   THIS SUBROUTINE COMPUTES :
 00101      4*     C     THE SECOND DERIVATIVE OF THE EQUALLY-SPACED ARRAY Y(N)
 00101      5*     C
 00103      6*          DIMENSION Y(N),D2Y(N)                                               2
 00104      7*          IF (N.LT.4) GO TO 2                                                 3
 00106      8*          DX2 = DX**2                                                         4
 00107      9*          D2Y(1) = (2.0*Y(1)-5.0*Y(2)+4.0*Y(3)-Y(4))/DX2                      5
 00110     10*          N1 = N-1                                                            6
 00111     11*          DO 1 I=2,N1                                                         7
 00114     12*        1 D2Y(I) = (Y(I+1)-2.0*Y(I)+Y(I-1))/DX2                               8
 00116     13*          D2Y(N) = (2.0*Y(N)-5.0*Y(N-1)+4.0*Y(N-2)-Y(N-3))/DX2                9
 00117     14*          RETURN                                                             10
 00120     15*        2 WRITE (6,3)                                                        11
 00122     16*        3 FORMAT (27HD2DX2 NOT ENOUGH NODAL PTS.,/)                          12
 00123     17*          RETURN                                                             13
 00124     18*          END                                                                14

       END OF COMPILATION:        NO  DIAGNOSTICS.


 @HDG,P  ****** EFFICY ******
```

```
@FOR,S ME*NASA5.EFFICY,ME*NASA5.EFFICY
FOR S9A-07/13/72-20:56:02 (0,)

   SUBROUTINE EFFICY     ENTRY POINT 000134

   STORAGE USED: CODE(1) 000161; DATA(0) 000131; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   POLY
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000007 116G     0001   000011 121G     0001   000040 132G     0001   000042 135G     0001   000073 146G
    0000 R 000064 A        0000 R 000104 AK       0000 R 000073 APR      0000 R 000000 C        0000 R 000050 COEF
    0000 R 000055 COEFF    0000 R 000043 COF      0000 I 000102 I        0000   000114 INJP$    0000 I 000103 J
    0000 I 000105 K        0003 R 000000 POLY


 00101           SUBROUTINE EFFICY (NC,NCPR,TSOTB,TB,ETA,ETAPR)
 00103           DIMENSION C(5,7),COF(5),COEF(5),COEFF(7),A(7),APR(7)
 00104           REAL NC,NCPR
 00105           DATA(C(I,2),I=1,5)/-1.I632,.1633405,-1.629484,3.735489,-2.75355/,
 00105          1 (C(I,3),I=1,5)/1.438967,-.5483718,5.091788,-11.26815,7.905002/,
 00105          2 (C(I,4),I=1,5)/-1.158833,.7783245,-6.866955,14.98945,-10.35581/,
 00105          3 (C(I,5),I=1,5)/.537,-.5282332,4.460133,-9.675815,6.65502/,
 00105          4 (C(I,6),I=1,5)/-.1294667,.1666654,-1.360822,2.94164,-2.020815/,
 00105          5 (C(I,7),I=1,5)/.01253334,-.01962952,.1562953,-.3370346,.2314797/
 00114           A(1)    =  1.0
 00115           DO 20  I=2,7
 00120           DO 10  J=1,5
 00123        10 COEF(J) =  C(J,I)
 00125        20 A(I)    =  POLY (5,COEF,TSOTB)
 00127           ETA     =  POLY (7,A,NC)
 00130           APR(1)  =  0.0
 00131           DO 40  I=2,7
 00134           DO 30  J=1,5
 00137           AK      =  J-1
 00140        30 COF(J)  =  AK*C(J,I)
 00142        40 APR(I)  =  -(1.0/TB)*POLY(5,COF,TSOTB)
 00144           COEFF(7)=  APR(7)*NC**4
 00145           DO 50  I=1,6
 00150           K       =  I+1
 00151           AK      =  I
 00152        50 COEFF(I)=  APR(I)*AK*A(K)*NCPR
 00154           ETAPR   =  POLY (7,COEFF,NC)
 00155           RETURN
 00156           END

     END OF COMPILATION:       NO  DIAGNOSTICS.
```

QHDG,P ****** ELAS/MPAL ******

```
@FOR,S ME*NASA5.ELAS/MPAL,ME*NASA5.ELAS/MPAL
FOR S9A-07/13/72-20:56:06 (0,)

   FUNCTION ELAS        ENTRY POINT 000055

   STORAGE USED: CODE(1) 000061; DATA(0) 000040; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000010 1F        0000 R 000006 DT        0000 R 000000 ELAS      0000   000032 INJP$      0000 R 000007 THETA
    0000 R 000005 T0        0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3          0000 R 000004 X4


00101      1*            FUNCTION ELAS(T)
00101      2*      C
00101      3*      C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*      C       MODULUS OF ELASTICITY AS A FUNCTION OF TEMPERATURE (R) OF
00101      5*      C             ALUMINUM 7075
00101      6*      C                                          UNITS LBF/SQ.FT
00101      7*      C             TEMP. GE. 300.0.AND.LE. 1200.0 R
00101      8*      C
00103      9*            DATA X1,X2,X3,X4 /10.71,-0.63,-0.115,-0.06/,T0,DT /459.67,200.0/
00112     10*            THETA = (T-T0)/DT
00113     11*            ELAS = (((X4*THETA+X3)*THETA+X2)*THETA+X1)*1.0E06
00114     12*            ELAS = ELAS*144.0
00115     13*            IF (T.GE.300.0.AND.T.LE.1200.0) RETURN
00117     14*            WRITE (6,1) T
00122     15*          1 FORMAT (1H0,59HMODULUS OF ELASTICITY OF ALUMINUM, TEMP. OUT OF RAN
00122     16*           1GE, T = ,F8.3,/)
00123     17*            RETURN
00124     18*            END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  ELAS/MPBR  ******
```

```
@FOR,S ME*NASA5.ELAS/MPBR,ME*NASA5.ELAS/MPBR
FOR S9A-07/13/72-20:56:10 (0,)

   FUNCTION ELAS        ENTRY POINT 000055

   STORAGE USED: CODE(1) 000061; DATA(0) 000040; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000010 1F        0000 R 000006 DT        0000 R 000000 ELAS      0000   000032 INJP$      0000 R 000007 THETA
    0000 R 000005 TO        0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3        0000 R 000004 X4


 00101             FUNCTION ELAS(T)
 00101        C
 00101        C       THIS FUNCTION SUBPROGRAM COMPUTES :
 00101        C     MODULUS OF ELASTICITY AS A FUNCTION OF TEMPERATURE (R) OF
 00101        C            BERYLIUM WITH 0.84-1.68 BEO
 00101        C                                       UNITS LBF/SQ.FT
 00101        C            TEMP. GE. 400.0 AND LE. 1700.0 R
 00101        C
 00103             DATA X1,X2,X3,X4 /44.36,-3.755,0.335,-0.53/,TO,DT /459.67,400.0/
 00112             THETA = (T-TO)/DT
 00113             ELAS = (((X4*THETA+X3)*THETA+X2)*THETA+X1)*1.0E06
 00114             ELAS = ELAS*144.0
 00115             IF (T.GE.400.0.AND.T.LE.1700.0) RETURN
 00117             WRITE (6,1) T
 00122           1 FORMAT (1H0,59HMODULUS OF ELASTICITY OF BERYLIUM, TEMP. OUT OF RAN
 00122            1GE, T = ,F8.3,/)
 00123             RETURN
 00124             END

        END OF COMPILATION:        NO  DIAGNOSTICS.


 @HDG,P  ****** ELAS/MPCU ******
```

```
@FOR,S ME*NASA5.ELAS/MPCU,ME*NASA5.ELAS/MPCU
FOR S9A-07/13/72-20:56:13 (0,)

   FUNCTION ELAS        ENTRY POINT 000055

   STORAGE USED: CODE(1) 000061; DATA(0) 000040; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000010 1F       0000 R 000006 DT       0000 R 000000 ELAS     0000   000032 INJP$     0000 R 000007 THETA
    0000 R 000005 T0       0000 R 000001 X1       0000 R 000002 X2       0000 R 000003 X3      0000 R 000004 X4


00101              FUNCTION ELAS(T)
00101       C
00101       C         THIS FUNCTION SUBPROGRAM COMPUTES :
00101       C        MODULUS OF ELASTICITY AS A FUNCTION OF TEMPERATURE (R) OF
00101       C               COPPER
00101       C                                         UNITS LBF/SQ.FT
00101       C               TEMP. GE. 400.0 AND LE. 1800.0 R
00101       C
00103              DATA X1,X2,X3,X4 /16.55,-0.4933,-1.935,0.2283/,T0,DT /459.67,400./
00112              THETA = (T-T0)/DT
00113              ELAS = (((X4*THETA+X3)*THETA+X2)*THETA+X1)*1.0E06
00114              ELAS = ELAS*144.0
00115              IF (T.GE.400.0.AND.T.LE.1800.0) RETURN
00117              WRITE (6,1) T
00122            1 FORMAT (1H0,57HMODULUS OF ELASTICITY OF COPPER, TEMP. OUT OF RANGE
00122             1, T = ,F8.3,/)
00123              RETURN
00124              END

      END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  EMIT/SCZ93  ******
```

```
****** EMIT/SCZ93 ******                                                        DATE 071372        PAGE     1

@FOR,S ME*NASA5.EMIT/SCZ93,ME*NASA5.EMIT/SCZ93
FOR S9A-07/13/72-20:56:16 (0,)

   FUNCTION EMIT        ENTRY POINT 000030

   STORAGE USED: CODE(1) 000035; DATA(0) 000016; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003    POLY
    0004    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001    000016 1L        0000 R 000001 A        0000 R 000000 EMIT      0000    000011 INJP$     0003 R 000000 POLY


00101          FUNCTION EMIT(T)
00101     C
00101     C  THIS SUBROUTINE COMPUTES :
00101     C    THE TOTAL HEMISPHERICAL EMITTANCE AS A FUNCTION OF THE SURFACE
00101     C    TEMPERATURE (R)
00101     C
00103          DIMENSION A(5)
00104          DATA  A(1),A(2),A(3),A(4),A(5)/0.8990103E+00, -0.1400633E-03,
00104        1      0.3879700E-06, -0.3937509E-09, 0.1015627E-12/
00112          IF(T.GE.1600.0) GO TO 1
00114          EMIT  = POLY(5,A,T)
00115          RETURN
00116        1 EMIT  = 0.228
00117          RETURN
00120          END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  ENTAIR  ******
```

```
@FOR,S ME*NASA5.ENTAIR,ME*NASA5.ENTAIR
FOR S9A-07/13/72-20:56:20 (0,)

   FUNCTION ENTAIR      ENTRY POINT 000204

   STORAGE USED: CODE(1) 000225; DATA(0) 000071; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   ALOG
    0004   SQRT
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000157 10L       0001   000103 5L        0000 R 000001 A         0000 R 000000 ENTAIR    0000 R 000032 ENTN
    0000 R 000033 ENTO      0000 R 000013 ENTO      0000 R 000015 ENTO0     0000 R 000007 FMN       0000 R 000006 FMO
    0000   000053 INJP$     0000 R 000031 TLOG      0000 R 000030 TMT       0000 R 000026 TMO       0000 R 000027 TOT
    0000 R 000012 TTO       0000 R 000014 TOO       0000 R 000022 TO2       0000 R 000023 TO3       0000 R 000024 TO4
    0000 R 000025 TO5       0000 R 000016 T2        0000 R 000017 T3        0000 R 000020 T4        0000 R 000021 T5
    0000 R 000011 WMN       0000 R 000010 WMO


00101            FUNCTION ENTAIR(T)
00101      C
00101      C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101      C        ENTHALPY OF AIR AS A FUNCTION OF TEMPERATURE (R)
00101      C                                      UNITS BTU/LBM
00101      C
00103            DIMENSION A(5)
00104            DATA A(1),A(2),A(3),A(4),A(5)/0.34240E+00,-0.95225E-03,
00104           1     0.31862E-05,-0.45750E-08,0.23750E-11/
00112            DATA FMO,FMN,WMO,WMN,TTO,ENTO/0.234559,0.765441,31.9988,28.0134,
00112           1 600.,143.47 /
00121            DATA TOO,ENTOO/300.,71.61/
00124            T2     = T**2
00125            T3     = T2*T
00126            T4     = T2*T2
00127            T5     = T2*T3
00130            TO2    = TOO**2
00131            TO3    = TO2*TOO
00132            TO4    = TO2*TO2
00133            TO5    = TO3*TO2
00134            TMO    = T-TOO
00135            TOT    = T/TTO
00136            TMT    = T-TTO
00137            TLOG   = LOG(TOT)
00140            IF (T .GT. 600.) GO TO 5
00142            ENTAIR = ENTOO+A(1)*TMO+(A(2)/2.)*(T2-TO2)+(A(3)/3.)*
00142           1        (T3-TO3)+(A(4)/4.)*(T4-TO4)+(A(5)/5.)*(T5-TO5)
00143            RETURN
```

```
    5 ENTN   = 9.47*TMT-3470.*TLOG-1.16E+06*(1./T-1./TT0)
      ENTO   = 11.515*TMT-344.*(SQRT(T)-SQRT(TT0))+1530.*TLOG
      IF (T .LT. 5000.) GO TO 10
      ENTO   = ENTO+5.E-05*((T2-TT0**2)/2.-4000.*TMT)
   10 ENTAIR  =  ENTO+FMO*ENTO/WMO+FMN*ENTN/WMN
      RETURN
      END

       END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
@HDG,P  ******  EXITAV  ******
```

```
@FOR,S ME*NASA5.EXITAV,ME*NASA5.EXITAV
FOR S9A-07/13/72-20:56:23 (0,)

   SUBROUTINE EXITAV    ENTRY POINT 000076

   STORAGE USED: CODE(1) 000110; DATA(0) 000030; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003    QRD     003721
    0004    QIN     001610
    0005    ABSRST  000601

   EXTERNAL REFERENCES (BLOCK, NAME)

    0006    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000012 111G       0001     000021 114G       0005 R 000000 ALPHFN     0005 R 000226 ALPHMP     0003     003465 CSF
    0003     003464 DXX2       0003     003472 DXX21      0003     003463 DZMFN      0003 R 003410 EBFN       0003 R 003441 EBMP
    0005 R 000461 EMITFN      0005 R 000512 EMITMP     0003 R 003467 EXTIFN     0003 R 003471 EXTIMP     0003 R 003466 EXTSFN
    0003 R 003470 EXTSMP      0005 R 000517 EXTVCT     0000 I 000002 I          0000     000010 INJP$     0000 I 000003 J
    0000 I 000004 K           0003     003461 LCT        0003     003462 LTT        0003     003460 MCVRD      0004     001605 NSRD
    0004     001604 NTM        0004     000454 QIFN       0004     001274 QITB       0004     000144 QSFN       0004     000764 QSTB
    0004     001606 QTO        0003     003473 SS         0003     003670 SSTT       0004     000000 TM         0003     000000 TRMTX
    0004     001607 TX         0003     003446 XX2        0000 R 000000 ZFN        0000 R 000001 ZMP        0003     003453 ZZ2


 00101          SUBROUTINE EXITAV
 00101      C
 00101      C THIS SUBROUTINE COMPUTES :
 00101      C   THE EXITATION VECTOR NECESSARY FOR THE CALCULATION OF THE INCIDENT
 00101      C   NET RADIANT FLUX
 00101      C
 00103          COMMON /QRD/ TRMTX(30,60),EBFN(5,5),EBMP(5),XX2(5),ZZ2(5),
 00103         1            MCVRD,LCT,LTT,DZMFN,
 00103         2            DXX2,CSF,EXTSFN,EXTIFN,EXTSMP,EXTIMP,DXX21,SS(5,5,5)
 00103         3            ,SSTT(5,5)
 00104          COMMON /QIN/TM(100), QSFN(100,2), QIFN(100,2), QSTB(100,2),
 00104         1            QITB(100,2), NTM, NSRD, QTO, TX
 00105          COMMON /ABSRST/ALPHFN(5,5,6),ALPHMP(5,31),EMITFN(5,5),EMITMP(5),
 00105         1                 EXTVCT(50)
 00106          ZFN    = EXTSFN+EXTIFN
 00107          ZMP    = EXTSMP+EXTIMP
 00110          DO 16 I=1,5
 00113          DO 15 J=1,5
 00116          K      =(I-1)*5 +J
 00117       15 EXTVCT(K) = EMITFN(J,I)*EBFN(J,I)+(1.0-ALPHFN(I,J,6))*ZFN
 00121          K      =I+25
 00122       16 EXTVCT(K) = EMITMP(I)*EBMP(I)+(1.0-ALPHMP(I,31))*ZMP
```

```
00124     23*          RETURN
00125     24*          END

       END OF COMPILATION:        NO  DIAGNOSTICS.

@HDG,P  ******  FINT  ******
```

```
@FOR,S ME*NASA5.FINT,ME*NASA5.FINT
FOR S9A-07/13/72-20:56:25 (0,)

   SUBROUTINE FINT      ENTRY POINT 000075

   STORAGE USED: CODE(1) 000111; DATA(0) 000027; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000043 111G      0000 R 000000 DDX       0000   000010 INJP$     0000 I 000001 J


00101          SUBROUTINE FINT(Y,Y0,DX,N,F)
00101     C
00101     C  THIS SUBROUTINE COMPUTES :
00101     C    THE INDEFINITE INTEGRAL BY SIMPSONS RULE OF THE EQUALLY-SPACED
00101     C    ARRAY Y(N)
00101     C
00103          DIMENSION Y(N),F(N)
00104          F(1) = Y0
00105          DDX = DX/24.
00106          F(2) = F(1)+DDX*(9.*Y(1)+19.*Y(2)-5.*Y(3)+Y(4))
00107          F(3) = F(2)+DDX*(-Y(1)+13.*(Y(2)+Y(3))-Y(4))
00110          DO 1 J=4,N
00113        1 F(J) = F(J-1)+DDX*(9.*Y(J)+19.*Y(J-1)-5.*Y(J-2)+Y(J-3))
00115          RETURN
00116          END
      END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  FLSTRT  ******
```

```
******  FLSTRT  ******                                                          DATE 071372        PAGE     1

@FOR,S ME*NASA5.FLSTRT,ME*NASA5.FLSTRT
FOR S9A-07/13/72-20:56:28 (0,)

   SUBROUTINE FLSTRT     ENTRY POINT 000231

   STORAGE USED: CODE(1) 000245; DATA(0) 000233; BLANK COMMON(2) 001115

    COMMON BLOCKS:

    0003    DVCMFL 000002
    0004    FLCMP  000024

   EXTERNAL REFERENCES (BLOCK, NAME)

    0005    DERIVL
    0006    CNTLN
    0007    RHOF
    0010    CPF
    0011    TRNSPT
    0012    DDX
    0013    RKSF
    0014    NERR2$
    0015    NWDU$
    0016    NIO2$
    0017    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000046 10L       0000     000051 115F      0000     000127 120F      0001     000076 15L       0001     000120 20L
    0001     000143 25L       0001     000010 5L        0000 R 000006 AL         0002     000562 AUX2      0006 R 000000 CNTLN
    0002     000752 COB       0002     001107 COH       0002     000574 CONFN     0002     000740 CONMP     0010 R 000000 CPF
    0002 R 001070 CPO         0002     001072 DELTA     0000 R 000014 DELY       0005 R 000000 DERIVL     0002     000764 DOB
    0004 R 000000 DTHETA      0002     001110 DXI       0002     001053 DXIMP     0002     001052 DXITB     0000 R 000003 DY
    0000 R 000030 DYST        0002 R 001051 DZ         0002     001103 FENTH     0002     001045 FFO       0002     001101 FLUX
    0003     000001 FLUXI     0002 R 001041 FMACH      0002 R 001040 FNU        0002     001046 FOF       0002     000012 FP
    0002 R 001042 FPR         0002 R 001037 FR         0002     001050 FRAD      0002     001111 FRO       0002     001036 FRE
    0002     001104 FREJ      0002     001043 FRL       0002     001044 FRM       0002 R 000036 FT         0000 R 000047 FT1
    0002     000024 FW        0002     001113 FXHW      0002     001112 FXOH      0002 R 001047 FZ         0002     001105 HFN
    0000 I 000043 IBKP        0000 I 000045 IERR       0002 I 001003 IFLOW      0000     000223 INJP$     0000 I 000042 ISTP
    0002     001024 LC        0002     001032 LIM       0002     001031 LIMWRT    0002     001011 LL1       0002     001012 LL2
    0002     001013 LL3       0002     001014 LL4       0002     001015 LL5       0002     001016 LL6       0002     001017 LL7
    0002     001006 LMP       0002     001004 LT        0002     001005 LTB       0002     001007 LTBMZ     0002     001010 LTB2MZ
    0002     001030 MM1       0002     001033 MOD       0002     001025 MSTOTR    0002 I 000777 MZ         0002     001034 NCCZ
    0002     001035 NCONV     0002 I 001002 NCTL       0002     001026 NCTM      0000 I 000046 NEQ        0002     001023 NEQUS
    0002     001027 NM1       0002     001001 NRMP      0002     001020 NRMP1     0002     001022 NRMP2     0002     001000 NRTB
    0002     001021 NRTB1     0000 I 000044 NTRY       0002     000776 NX        0000 R 000017 PD         0002     001063 PHIF
    0002     001062 PHIM      0002     001071 PI        0002 R 001065 P0         0002     001102 QREF      0002     000360 QRFN
    0002     000524 QRMP      0002     001074 RDTWRT    0007 R 000000 RHOF       0002     001114 RHOFN     0002 R 001067 RHO0
    0000 R 000011 RL          0002     001073 RLIMIT    0002     001100 RTEND     0000 R 000022 SO         0002     000132 TEMP
    0002 R 001077 TI          0002     001076 TINTL     0002     000276 TMP       0002     001075 TREF      0002     000050 TW
    0002 R 001064 T0          0003 R 000000 WRAT       0002 R 001066 W0         0002     000536 XIFN      0002     000005 XIMP
    0002     000000 XITB      0002     001106 XL        0000 R 000050 XP         0002     001054 XRE       0002     001057 XX10
    0002     001060 XX11      0002     001061 XX12      0002     001055 XX3       0002     001056 XX4       0000 R 000000 Y
```

```
     0000 R 000025 YS        0000 R 000036 YSIMP     0000 R 000033 YST       0000 R 000041 Z         0002    000550 ZETA

00101          SUBROUTINE FLSTRT(RE,PRL,DLTA)
00101     C
00101     C THIS SUBROUTINE PROVIDES :
00101     C    1- FLUID FLOW (INITIAL AND CURRENT) CONDITIONS
00101     C    2- TABLE HEADING FOR INITIAL CONDITIONS
00101     C
00103          COMMON XITB(5),XIMP(5),FP(10),FW(10),FT(10),TW(10,5),TEMP(10,10),
00103         1        TMP(10,5),QRFN(10,10),QRMP(10),XIFN(10),ZETA(10),AUX2(10),
00103         2        CONFN(10,10),CONMP(10),COB(10),DOB(10)
00104          COMMON NX,MZ,NRTB,NRMP,NCTL,IFLOW,LT,LTB,LMP,LTBMZ,LTB2MZ,LL1,
00104         1       LL2,LL3,LL4,LL5,LL6,LL7,NRMP1,NRTB1,NRMP2,NEQUS,LC,MSTOTR,
00104         2       NCTM,NM1,MM1,LIMWRT,LIM,MOD,NCCZ,NCONV
00105          COMMON FRE,FR,FNU,FMACH,FPR,FRL,FRM,FFO,FOF,FZ,FRAD,DZ,DXITB,DXIMP
00105         1        ,XRE,XX3,XX4,XX10,XX11,XX12,PHIM,PHIF,T0,P0,W0,RHO0,CP0,PI
00105         2        ,DELTA,RLIMIT,RDTWRT,TREF,TINTL,TI,RTEND,FLUX,QREF,FENTH,
00105         3        FREJ,HFN,XL,COH,DXI,FRD,FXOH,FXHW,RHOFN
00106          COMMON /DVCMFL/ WRAT,FLUXI
00107          COMMON /FLCMP/ DTHETA(20)
00107     C
00110          DIMENSION Y(3),DY(3),AL(3),RL(3),DELY(3),PD(3),SD(3),YS(3),             04
00110         1          DYST(3),YST(3),YSIMP(3)                                      05
00111          EXTERNAL DERIVL,CNTLN                                                  06
00111     C
00112          GO TO (5,10), IFLOW
00113        5 RHO0 = RHOF(P0,T0)                                                     08
00114          CP0 =  CPF(RHO0,T0)
00115          FPR = P0/(RHO0*W0**2)                                                  09
00116          FZ = P0/(RHO0*T0*CP0*778.16)
00117          FMACH   = W0**2/(T0*CP0*778.16)
00120       10 CALL TRNSPT (RE,PRL,DLTA,FR,FNU)
00120     C                                                                          012
00120     C    INITIALIZATION                                                        013
00121          Z    = 0.0
00122          ISTP = 1                                                               016
00123          IBKP = 1                                                               017
00124          NTRY = 1                                                               018
00125          IERR = 0                                                               019
00126          NCTL = 1                                                               020
00127          Y(1) = 1.0
00130          GO TO (15,20),IFLOW
00131       15 Y(2) = RHO0/RHOF(P0,TI)*WRAT
00132          Y(3) = FT(1)
00133          NEQ  = 3
00134          WRITE (6,115)
00136          GO TO 25
00137       20 FT1  = FT(1)*T0
00140          Y(2) = RHO0/RHOF(P0,FT1)*WRAT
00141          NEQ  = 2
00142          CALL DDX(FT,DTHETA,DZ,MZ)
00143       25 CALL RKSF (DERIVL,CNTLN,Y,DY,AL,RL,Z,DZ,NEQ,ISTP,IBKP,NTRY,
00143         1          IERR,DELY,PD,SD,YS,YST,DYST,YSIMP)                           031
00144          IF(IFLOW.EQ.2) RETURN
```

```
00146            XP    = FPR/2.0                                                   032
00147            WRITE (6,120) PO,WO,TO,RE,PRL,DLTA,XP
00160            IFLOW   = 2
00161            RETURN                                                            041
00162        115 FORMAT(1H1,15X,23HINITIAL LINE CONDITIONS,/,16X,23H******* **** **   25
00162           1********,/,25X,31H(ALL QUANTITIES ARE NORMALIZED),/,83X,5HFLUID,15   026
00162           2X,4HWALL,/,15X,16HPT.NO.  POSITION,11X,8HPRESSURE,12X,8HVELOCITY,    027
00162           311X,11HTEMPERATURE,9X,11HTEMPERATURE,/,26X,1HZ,18X,1HP,19X,1HW,19X   028
00162           4,1HT,18X,3HTWI,/)                                                029
00163        120 FORMAT(1H0,5X,25HINLET PRESSURE     PO  =  ,F10.3,11H  LBF/SQ.FT,/,   034
00163           1            6X,25HREF.  VELOCITY    WO  =  ,F10.5,11H  FT/SEC    ,/,  035
00163           2            6X,25HREF. TEMPERATURE TOO  =  ,F10.3,11H  R         ,//  036
00163           3            6X,25H      REYNOLDS NO     =  ,E20.5,/,
00163           4            6X,25H      PRANDTL  NO     =  ,F20.6,/,                  038
00163           5            6X,25H      DELTA           =  ,F20.6,/,
00163           6            6X,25H      REL.PRESSURE IS    ,E20.6,//)                 039
00163      C                                                                       040
00164            END                                                               042
```

END OF COMPILATION: NO DIAGNOSTICS.

@HDG,P ****** FMINV ******

```
@FOR,S ME*NASA5.FMINV,ME*NASA5.FMINV
FOR S9A-07/13/72-20:56:31 (0,)

   SUBROUTINE FMINV     ENTRY POINT 000254

   STORAGE USED: CODE(1) 000306; DATA(0) 001260; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000046 105G      0001   000151 11L       0001   000051 111G      0001   000071 117G      0001   000104 123G
    0001   000125 133G      0001   000130 137G      0001   000172 150G      0001   000175 154G      0001   000227 164G
    0001   000212 20L       0000 R 001214 AA        0000 R 001217 B         0000 I 001212 I         0000   001224 INJP$
    0000 I 001215 I1        0000 I 001220 I2        0000 I 001213 J         0000 I 001216 K         0000 R 000000 XMAT


00101              SUBROUTINE FMINV (A,X,N,M)
00103              DIMENSION A(N,N),X(N),XMAT(25,26)
00104              DO 1 I=1,N
00107              XMAT(I,M) = X(I)
00110              DO 1 J=1,N
00113            1 XMAT(I,J) = A(I,J)
00116              DO 20 I=1,N
00121              AA = XMAT(I,I)
00122              DO 5 J=1,M
00125            5 XMAT(I,J) = XMAT(I,J)/AA
00127              IF (I.EQ.1) GO TO 11
00131              I1 = I-1
00132              DO 10 K=1,I1
00135              B = XMAT(K,I)
00136              DO 10 J=1,M
00141           10 XMAT(K,J) = XMAT(K,J) - XMAT(I,J) * B
00144              IF (I.EQ.N) GO TO 20
00146           11 I2 = I+1
00147              DO 15 K=I2,N
00152              B = XMAT(K,I)
00153              DO 15 J=1,M
00156           15 XMAT(K,J) = XMAT(K,J) - XMAT(I,J) * B
00161           20 CONTINUE
00163              DO 25 I=1,N
00166           25 X(I) = XMAT(I,M)
00170              RETURN
00171              END

        END OF COMPILATION:        NO  DIAGNOSTICS.
```

QHDG,P ****** HFL/CFFC43 ******

```
****** HFL/CFFC43 ******                                                           DATE 071372        PAGE     1

@FOR,S ME*NASA5.HFL/CFFC43,ME*NASA5.HFL/CFFC43
FOR S9A-07/13/72-20:56:34 (0,)

   FUNCTION HFL          ENTRY POINT 000022

   STORAGE USED: CODE(1) 000024; DATA(0) 000014; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000000 HFL        0000   000007 INJP$      0000 R 000004 THETA      0000 R 000003 TO          0000 R 000001 X1
    0000 R 000002 X2


 00101      1*               FUNCTION HFL(RHO,T)
 00101      2*      C           ENTHALPY AS A FUNCTION OF DENSITY (SLUG/CU.FT) AND
 00101      3*      C                 TEMPERATURE (R) OF FC-43
 00101      4*      C                                         UNITS BTU/SLUG
 00103      5*               DATA X1,X2 /-0.020092,5.4054E-04/,TO /401.67/
 00107      6*               THETA = T-TO
 00110      7*               HFL   = (X1+X2*(T+TO)/2.0)*THETA*32.174
 00111      8*               RETURN
 00112      9*               END

      END OF COMPILATION:        NO  DIAGNOSTICS.

 @HDG,P  ******  HFL/CFFC75  ******
```

```
@FOR,S ME*NASA5.HFL/CFFC75,ME*NASA5.HFL/CFFC75
FOR S9A-07/13/72-20:56:36 (0,)

   FUNCTION HFL          ENTRY POINT 000022

   STORAGE USED: CODE(1) 000024; DATA(0) 000014; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000000 HFL       0000    000007 INJP$     0000 R 000004 THETA     0000 R 000003 T0        0000 R 000001 X1
    0000 R 000002 X2


 00101      1*          FUNCTION HFL(RHO,T)
 00101      2*     C
 00101      3*     C       THIS FUNCTION SUBPROGRAM COMPUTES :
 00101      4*     C       ENTHALPY AS A FUNCTION OF DENSITY (SLUG/CU.FT) AND
 00101      5*     C            TEMPERATURE (R) OF FC-75
 00101      6*     C                                    UNITS BTU/SLUG
 00101      7*     C
 00103      8*          DATA X1,X2 /0.115082,2.4333E-04/,T0 /324.67/
 00107      9*          THETA = T-T0
 00110     10*          HFL   = (X1+X2*(T+T0)/2.0)*THETA*32.174
 00111     11*          RETURN
 00112     12*          END

      END OF COMPILATION:        NO  DIAGNOSTICS.


 @HDG,P  ******  HFL/CFHE  ******
```

```
@FOR,S ME*NASA5.HFL/CFHE,ME*NASA5.HFL/CFHE
FOR S9A-07/13/72-20:56:37 (0,)

   FUNCTION HFL          ENTRY POINT 000110

   STORAGE USED: CODE(1) 000124; DATA(0) 000047; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   PF
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000005 A        0000 R 000002 A1       0000 R 000003 B1       0000 R 000004 C        0000 R 000016 DRHO
    0000 R 000017 DRHO2    0000 R 000013 DT       0000 R 000015 DTM2     0000 R 000000 HFL      0000   000034 INJP$
    0000 R 000022 P        0003 R 000000 PF       0000 R 000001 R        0000 R 000011 RHOX     0000 R 000010 RHO0
    0000 R 000014 TM2      0000 R 000012 TX       0000 R 000007 T0       0000 R 000021 UFL      0000 R 000006 U0
    0000 R 000020 Y


00101             FUNCTION HFL(RHO,T)
00101       C
00101       C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101       C        ENTHALPY AS A FUNCTION OF DENSITY (SLUG/CU.FT) AND
00101       C             TEMPERATURE (R) OF HELIUM
00101       C                                         UNITS BTU/SLUG
00101       C
00103             DATA R,A1,B1,C,A /2077.02,136.9595,3.5002295E-03,10.000658,1.49610
00103            13E-02/,U0,T0,RHO0 /39922.0,10.938889,4.669193/
00114             RHOX = RHO*515.4275
00115             TX   = T/1.8
00116             DT   = TX-T0
00117             TM2  = 1.0/(TX*TX)
00120             DTM2 = 1.0/(T0*T0)-TM2
00121             DRHO = RHO0-RHOX
00122             DRHO2= RHOX*RHOX-RHO0*RHO0
00123             Y    = 3.0*R*C*TM2
00124             UFL  = U0+R*(1.5*DT+141.22973*DTM2)+(Y+A1)*DRHO-(Y*B1-A1*A)*DRHO2/
00124            12.0
00125             P    = PF(RHO,T)
00126             HFL  = UFL*0.013844+P/(RHO*778.26)
00127             RETURN
00130             END

        END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  HFL/CFNAK,  ******
```

```
@FOR,S ME*NASA5.HFL/CFNAK,ME*NASA5.HFL/CFNAK
FOR S9A-07/13/72-20:56:40 (0,)

   FUNCTION HFL          ENTRY POINT 000100

   STORAGE USED: CODE(1) 000112; DATA(0) 000037; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   CAPPA
    0004   PF
    0005   ALOG
    0006   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000017 C         0003 R 000000 CAPPA     0000 R 000010 C1        0000 R 000011 C2        0000 R 000007 DT
    0000 R 000000 HFL       0000 R 000014 H1        0000 R 000020 H2        0000   000030 INJP$     0004 R 000000 PF
    0000 R 000012 P0        0000 R 000016 P1        0000 R 000013 THETA     0000 R 000015 TK        0000 R 000006 T0
    0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3        0000 R 000004 X4        0000 R 000005 X5


00101           FUNCTION HFL(RHO,T)
00101      C
00101      C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101      C       ENTHALPY AS A FUNCTION OF DENSITY (SLUG/CU.FT) AND
00101      C            TEMPERATURE (R) OF NAK 78.6
00101      C                                    UNITS BTU/SLUG
00101      C
00103           DATA X1,X2,X3,X4,X5 /0.2255,-0.016292,0.005396,-0.000758,0.000054/
00103          1,T0,DT /469.67,300.0/,C1,C2 /58.773064,-0.008433/,P0 /2116.224/
00116           THETA = (T-T0)/DT
00117           H1    = ((((X5*THETA/5.0+X4/4.0)*THETA+X3/3.0)*THETA+X2/2.0)*THETA
00117          1+X1)*(T-T0)
00120           TK    = CAPPA(RHO,T)
00121           P1    = PF(RHO,T)-P0
00122           C     = C1+C2*T
00123           H2    = ((1.0+T*C2/C)*ALOG(1.0+TK*P1))/(C*TK*778.26)
00124           HFL   = (H1+H2)*32.174
00125           RETURN
00126           END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  HFL/CFSIL  ******
```

```
@FOR,S ME*NASA5.HFL/CFSIL,ME*NASA5.HFL/CFSIL
FOR S9A-07/13/72-20:56:42 (0,)

   FUNCTION HFL          ENTRY POINT 000300

   STORAGE USED: CODE(1) 000326; DATA(0) 000132; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003    PF
    0004    POLY
    0005    NWDU$
    0006    NI02$
    0007    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000     000051 1F       0000 R 000040 A        0000 R 000007 A1       0000 R 000041 A11      0000 R 000010 A2
    0000 R 000011 A3         0000 R 000012 A4       0000 R 000013 A5       0000 R 000042 B        0000 R 000014 B1
    0000 R 000043 B11        0000 R 000015 B2       0000 R 000016 B3       0000 R 000017 B4       0000 R 000020 B5
    0000 R 000044 C          0000 R 000021 C1       0000 R 000045 C11      0000 R 000022 C2       0000 R 000025 DT
    0000 R 000033 DT2        0000 R 000000 HFL      0000 R 000037 H1       0000 R 000050 H2       0000   000114 INJP$
    0000 R 000046 P          0003 R 000000 PF       0004 R 000000 POLY     0000 R 000047 P1       0000 R 000034 THETA
    0000 R 000035 THETA1     0000 R 000036 THETA2   0000 R 000023 T0       0000 R 000024 T01      0000 R 000032 T02
    0000 R 000026 X1         0000 R 000027 X2       0000 R 000030 X3       0000 R 000031 X4       0000 R 000001 Z


00101              FUNCTION HFL(RHO,T)
00101        C
00101        C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101        C        ENTHALPY AS A FUNCTION OF DENSITY (SLUG/CU.FT) AND
00101        C             TEMPERATURE (R) OF DOW CORNING 200 SILICON OIL (1 CS)
00101        C                                   UNITS BTU/SLUG
00101        C             TEMPERATURE .GE. 359.67 AND .LE. 859.67
00101        C
00103              DIMENSION Z(6)
00104              DATA A1,A2,A3,A4,A5 /12.35,2.98333,1.1,-0.48333,0.1/,B1,B2,B3,B4,B
00104             15 /-1.5,-0.01333,-1.18,0.57333,-0.1/,C1,C2 /0.7767,-0.0288/,T0,T01
00104             2,DT /559.67,609.67,50.0/,X1,X2,X3,X4 /0.46,0.00471,0.00141,0.00004
00104             33/,T02,DT2 /539.67,80.0/
00132              THETA  = (T-T0)/DT
00133              THETA1 = (T-T01)/DT
00134              THETA2 = (T-T02)/DT2
00135              H1   = (((X4*THETA2/4.0+X3/3.0)*THETA2+X2/2.0)*THETA2+X1)*(T-T02)
00136              A    = ((((A5*THETA+A4)*THETA+A3)*THETA+A2)*THETA+A1)*1.0E-06
00137              A11 = (((4.0*A5*THETA+3.0*A4)*THETA+2.0*A3)*THETA+A2)*(1.0E-06)/DT
00140              B    = ((((B5*THETA+B4)*THETA+B3)*THETA+B2)*THETA+B1)*1.0E-09
00141              B11 = (((4.0*B5*THETA+3.0*B4)*THETA+2.0*B3)*THETA+B2)*(1.0E-09)/DT
00142              C    = C1+C2*THETA1
00143              C11 = C2/DT
00144              P  = PF(RHO,T)
```

```
00145          P1 = P/144.0-14.696
00146          Z(1)= 0.0
00147          Z(2)= 1+T*C11/C
00150          Z(3)= (A11*T-A*Z(2))/2.0
00151          Z(4)= (T*(B11-A*A11)-B*Z(2))/6.0 .
00152          Z(5)= -(A*B11+A11*B)*T/8.0
00153          Z(6)= -B*B11*T/20.0
00154          H2  = POLY(6,Z,P1)
00155          HFL = (H1+H2/(C*337.37))*32.174
00156          IF (T.LT.360.67.OR.T.GT.860.67.OR.P.GT.146116.224.OR.P.GT.110116.2
00156         124.AND.T.LT.460.67) WRITE(6,1) T,P
00163        1 FORMAT (1H0,43HENTHALPY OF SILICON OIL, OUT OT RANGE, T = ,F10.5,6
00163         1H, P = ,F15.5,/)
00164          RETURN
00165          END
```

END OF COMPILATION: NO DIAGNOSTICS.

@HDG,P ****** INTERP ******

```
@FOR,S ME*NASA5.INTERP,ME*NASA5.INTERP
FOR S9A-07/13/72-20:56:45 (0,)

   SUBROUTINE INTERP    ENTRY POINT 000171

   STORAGE USED: CODE(1) 000226; DATA(0) 000063; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   YINT
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000037 105G      0001   000054 110G      0001   000062 115G      0001   000106 124G      0001   000122 127G
    0001   000130 134G      0000 I 000012 I         0000   000022 INJP$     0000 I 000014 J         0000 I 000013 K
    0000 R 000015 P         0003 R 000000 YINT      0000 R 000000 YY


 00101      1*             SUBROUTINE INTERP(NX1,MZ1,XX1,ZZ1,YY1,NX2,MZ2,XX2,ZZ2,YY2)
 00101      2*       C
 00101      3*       C   THIS SUBROUTINE MAPS A TWO-DIMENSIONAL FUNCTION YY1 FROM ONE GRID
 00101      4*       C   (XX1,ZZ1) ONTO ANOTHER TWO-DIMENSIONAL FUNCTION YY2 WITH ANOTHER GRID
 00101      5*       C   (XX2,ZZ2)
 00101      6*       C     NX1,MZ1  NUMBER OF NODAL POINTS OF THE ORIGINAL GRID (EACH LESS
 00101      7*       C              THAN OR EQUAL TO 10)
 00101      8*       C     NX2,MZ2  NUMBER OF NODAL POINTS OF THE NEW GRID (EACH LESS THAN
 00101      9*       C              OR EQUAL TO 10)
 00101     10*       C
 00103     11*             DIMENSION XX1(NX1), ZZ1(MZ1), YY1(10,10), YY(10), XX2(NX2),
 00103     12*            1          ZZ2(MZ2), YY2(10,10)
 00104     13*             DO 2 I  = 1,NX1
 00107     14*             DO 1 K  = 1,MZ1
 00112     15*           1 YY(K)   = YY1(K,I)
 00114     16*             DO 2 J  = 1,MZ2
 00117     17*             P       = ZZ2(J)
 00120     18*           2 YY2(J,I)= YINT(ZZ1,YY,MZ1,3,P)
 00123     19*             DO 4 J  = 1,MZ2
 00126     20*             DO 3 K  = 1,NX1
 00131     21*           3 YY(K)   = YY2(J,K)
 00133     22*             DO 4 I  = 1,NX2
 00136     23*             P       = XX2(I)
 00137     24*           4 YY2(J,I)= YINT(XX1,YY,NX1,3,P)
 00142     25*             RETURN
 00143     26*             END

        END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  MAIN  ******
```

```
@FOR,S ME*NASA5.MAIN,ME*NASA5.MAIN
FOR S9A-07/13/72-20:56:47 (0,)

  MAIN PROGRAM

  STORAGE USED: CODE(1) 003774; DATA(0) 006145; BLANK COMMON(2) 001115

   COMMON BLOCKS:

   0003   ADBH    000352
   0004   DVM     000002
   0005   VELALT  001132
   0006   CNV     000010
   0007   QRD     003721
   0010   QIN     001610
   0011   TC      000042
   0012   ABSRST  000601
   0013   SSF     000010
   0014   GEOM    000020
   0015   FLDINL  000457
   0016   DVCMFL  000002

  EXTERNAL REFERENCES (BLOCK, NAME)

   0017   DERIVM
   0020   CNTLM
   0021   TCALC
   0022   CLOSE
   0023   ADIABH
   0024   QINCID
   0025   TK
   0026   RHOF
   0027   VISC
   0030   CPF
   0031   THCF
   0032   HFL
   0033   FLSTRT
   0034   THCTB
   0035   THCMP
   0036   DEFINT
   0037   SHAPEF
   0040   RKS
   0041   NINTR$
   0042   NRNL$
   0043   NWDU$
   0044   NI01$
   0045   NI02$
   0046   NRDU$
   0047   NRBU$
   0050   NWBU$
   0051   NWNL$
   0052   SQRT
   0053   ASIN
   0054   NSTOP$
```

STORAGE ASSIGNMENT . (BLOCK, TYPE, RELATIVE LOCATION, NAME)

```
0000   005361 1055F     0001   002064 1076G     0001   001320 1100L     0001   002075 1104G     0001   002104 1112G
0001   002113 1120G     0001   002203 1140G     0001   002245 1151G     0000   005372 1155F     0001   002275 1163G
0001   000732 12L       0001   002730 1246G     0001   002731 1251G     0000   005403 1255F     0001   002735 1256G
0001   002742 1264G     0001   003113 1324G     0000   005406 1355F     0001   003360 1410G     0001   003363 1413G
0001   003431 1424G     0001   003434 1427G     0001   003477 1440G     0001   003506 1443G     0001   003530 1452G
0000   005425 1455F     0001   003537 1461G     0001   003662 1500G     0000   005167 155F      0000   005436 1555F
0000   005454 16F       0000   005447 2F        0001   000136 200L      0001   000032 2000L     0001   001360 2100L
0000   005455 22F       0001   000120 227G      0001   000160 237G      0001   001110 24L       0001   000161 242G
0001   000221 254G      0000   005207 255F      0001   000235 263G      0001   001167 28L       0000   005450 3F
0001   001217 30L       0001   000141 300L      0001   002761 312L      0000   005457 313F      0001   003107 314L
0001   000336 316G      0000   005476 320F      0000   005722 321F      0001   000364 325G      0001   000410 337G
0001   001472 34L       0001   003461 341L      0001   000426 346G      0000   005243 355F      0001   000444 355G
0001   000456 363G      0001   003656 364L      0001   000474 372G      0000   005452 4F        0001   000506 400G
0001   000524 407G      0001   000552 416G      0001   000564 424G      0001   000576 432G      0001   000610 440G
0000   005257 455F      0001   000644 455G      0001   000656 463G      0001   000670 472G      0001   000702 500G
0001   000171 500L      0001   000714 506G      0001   000726 514G      0001   000764 535G      0001   001012 543G
0001   001022 550G      0001   001030 554G      0000   005274 555F      0001   001036 560G      0001   001053 571G
0001   001070 603G      0000   005310 655F      0001   001211 665G      0001   001247 676G      0001   001255 703G
0001   001315 715G      0001   001336 722G      0001   001345 727G      0001   001416 740G      0000   005320 755F
0001   000614 8L        0001   000240 800L      0000   005332 855F      0000   005344 955F      0000   006017 9998F
0001   003770 9999L     0000 R 000621 A         0011 R 000003 ABEMF     0000 R 004355 AITB      0003 R 000001 AL
0000 R 004270 ALIMIT    0013   000002 ALPFN     0000 R 004256 ALPHA     0012   000000 ALPHFN    0012   000226 ALPHMP
0005 R 000310 ALTA      0005 R 000454 ALTR      0000 R 004265 AMAN      0000 R 004264 AN        0000 R 004300 ANGINC
0000 R 004263 ATM       0000 R 004371 ATOT      0002   000562 AUX2      0000 R 004361 BIOTNO    0000 R 004350 BOL
0000 R 004257 BTA       0020 R 000000 CNTLM     0002 R 000752 COB       0006 R 000007 COEFF     0002 R 001107 COH
0003   000161 COMFL     0002 R 000574 CONFN     0003   000173 CONFNA    0002 R 000740 CONMP     0003   000147 CP
0030 R 000000 CPF       0002 R 001070 CP0       0007   003465 CSF       0013 R 000002 CTA       0003 R 000000 D
0036 R 000000 DEFINT    0002 R 001072 DELTA     0000 R 001441 DELY      0017 R 000000 DERIVM    0000 R 004325 DITB
0000 R 004241 DITBI     0002 R 000764 DOB       0000 R 004347 DTA       0003   000326 DTL       0000 R 004401 DTME
0000 R 004266 DTWRTE    0006 R 000003 DX        0002 R 001110 DXI       0000 R 004344 DXIFN     0002 R 001053 DXIMP
0002 R 001052 DXITB     0007 R 003464 DXX2      0007 R 003472 DXX21     0000 R 000311 DY        0000 R 003101 DYST
0002 R 001051 DZ        0007 R 003463 DZMFN     0007   003410 EBFN      0007   003441 EBMP      0003 R 000244 EFF
0003   000205 EMIS      0012   000461 EMITFN    0012   000512 EMITMP    0007   003467 EXTIFN    0007   003471 EXTIMP
0007   003466 EXTSFN    0007   003470 EXTSMP    0012   000517 EXTVCT    0002 R 001103 FENTH     0002 R 001045 FFO
0000   004600 FIN       0000   004444 FINA      0015   000456 FLDINT    0000 R 004364 FLMASI    0014 R 000016 FLMASS
0000   004565 FLOW      0000 R 004316 FLU       0000 R 004317 FLUID     0000   004457 FLUIDA    0002 R 001101 FLUX
0016 R 000001 FLUXI     0002   001041 FMACH     0000 R 004314 FNM       0000 R 004365 FNMASI    0000 R 004362 FNMASS
0000 R 004315 FNMTL     0002 R 001040 FNU       0002 R 001046 FOF       0002 R 000012 FP        0002   001042 FPR
0002   001037 FR        0002 R 001050 FRAD      0002 R 001111 FRD       0002 R 001036 FRE       0002 R 001104 FREJ
0002 R 001043 FRL       0002 R 001044 FRM       0002 R 000036 FT        0002 R 000024 FW        0002 R 001113 FXHW
0002 R 001112 FXOH      0002   001047 FZ        0000 R 004260 GAMMA     0000   004750 GINPT     0003 R 000013 H
0003 R 000231 HAB       0000 R 004231 HDG       0032 R 000000 HFL       0000 R 004356 HFLO      0002 R 001105 HFN
0000 R 004246 HFMI      0000 I 004301 I         0000 I 004404 IBKP      0011 I 000001 ICASE     0000 I 004405 IERR
0002 I 001003 IFLOW     0000 I 004403 IFVD      0000 I 004304 IH1       0000 I 004305 IH2       0006 I 000002 IOPTN
0000 I 004237 ISYM      0000 I 004323 IT        0011 I 000000 ITAPE     0000 I 004276 IU        0000 I 004322 IUL
0000 I 004277 IW        0000 I 004324 I1        0000 I 004302 J         0000 I 004311 K         0000 I 004307 K1
0000 I 004310 K2        0002 I 001024 LC        0007 I 003461 LCT       0015 I 000001 LFLD      0002 I 001032 LIM
0002 I 001031 LIMWRT    0002 I 001011 LL1       0002 I 001012 LL2       0002 I 001013 LL3       0002 I 001014 LL4
0002 I 001015 LL5       0002 I 001016 LL6       0002 I 001017 LL7       0002 I 001006 LMP       0002 I 001004 LT
0002 I 001005 LTB       0000 I 004376 LTBJ      0002 I 001007 LTBMZ     0002 I 001010 LTB2MZ    0000 I 004271 LTS
0007 I 003462 LTT       0003 R 000064 M         0000   004700 MANIFD    0007 I 003460 MCVRD     0002 R 001101 MDOT
0000 R 000000 MDOTI     0000 I 004345 MMEP      0002 I 001030 MM1       0002 I 001033 MODA      0000   004474 MRI
0000 I 004272 MRSTRT    0002 I 001025 MSTOTR    0002 I 000777 MZ        0005 I 001130 NA        0002 I 001034 NCCZ
0002 I 001035 NCONV     0002   001002 NCTL      0002 I 001026 NCTM      0002 I 001023 NEQUS     0015 I 000000 NFLDTA
0002 I 001027 NM1       0005 I 001131 NR        0002 I 001001 NRMP      0002 I 001020 NRMP1     0002 I 001022 NRMP2
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0002 I 001000 NRTB      0000 I 004244 NRTBI     0002 I 001021 NRTB1     0000 I 004306 NS        0006 I 000004 NSRAD
0010 I 001605 NSRD      0003 I 000076 NT        0014 I 000012 NTBS      0000 I 004274 NTF       0010 I 001604 NTM
0000 I 004402 NTRY      0000 I 004275 NT1       0002 I 000776 NX        0000 R 001751 PD        0000 R 004372 PFLD
0000 R 004261 PHI       0002 R 001063 PHIF      0002 R 001062 PHIM      0011 R 000004 PHIN      0000 R 004240 PHN
0002 R 001071 PI        0003 R 000052 PIN       0000 R 004367 PLMASI    0014 R 000015 PLMASS    0000 R 004354 PRLNTL
0000 R 004320 PRO       0000 R 004255 PROB      0000 R 004321 PROMTL    0000   004627 PROTLR    0002 R 001065 PO
0010 R 000454 QIFN      0010   001274 QITB      0000   004515 QNML      0003   000314 QOUT      0002 R 001102 QREF
0002   000360 QRFN      0002   000524 QRMP      0010 R 000144 QSFN      0010 R 000764 QSTB      0010 R 001606 QTO
0000 R 001131 R         0002 R 001074 RDTWRT    0000 R 004353 REY       0026 R 000000 RHOF      0000 R 004374 RHOFLD
0002 R 001114 RHOFN     0000 R 004250 RHOFNI    0000 R 004352 RHOI      0000 R 004252 RHOMET    0000 R 004334 RHOMP
0000 R 004251 RHOMPI    0000 R 004333 RHOTB     0000 R 004243 RHOTBI    0002 R 001067 RHOO      0000 R 004331 RITB
0002 R 001073 RLIMIT    0000 R 004332 ROTB      0002 R 001100 RTEND     0000   004705 RUNOPT    0013 R 000003 R1
0013 R 000000 R2        0000 R 002261 SD        0014 R 000000 SFN       0000 R 004273 SIDE      0000 R 004351 SLOPE
0000 R 004336 SMP       0006 R 000005 SMPC      0000 R 004327 SROOT     0000 R 004245 SROOTI    0000 R 004340 SRO2
0007   003473 SS        0007   003670 SSTT      0006 R 000000 STAGX     0000 R 004326 STB       0000 R 004242 STBI
0000 R 004330 STIP      0000 R 004247 STIPI     0014 R 000017 STR       0006 R 000006 ST4       0000   004410 SYSTEM
0013 R 000001 T         0005 R 000000 TA        0000 R 004254 TAU       0000 R 004357 TAVG      0003   000217 TB
0000 R 004312 TBM       0000 R 004366 TBMASI    0014 R 000014 TBMASS    0000 R 004313 TBMTL     0002 R 000132 TEMP
0000 R 004267 TEND      0000 R 004373 TFLD      0003 R 000026 TH        0031 R 000000 THCF      0035 R 000000 THCMP
0034 R 000000 THCTB     0000 R 004262 THETA     0002 R 001077 TI        0015 R 000146 TIFLD     0000 R 004400 TIME
0003 R 000040 TIN       0002 R 001076 TINTL     0025 R 000000 TK        0003   000270 TL        0010 R 000000 TM
0015 R 000002 TMEFLD    0002 R 000276 TMP       0000 R 004335 TNN       0014 R 000013 TNXL      0011 R 000002 TO
0000 R 004346 TOL       0000 R 004370 TOTMSI    0000 R 004363 TOTMSS    0003 R 000340 TOUT      0005 R 000144 TR
0002 R 001075 TREF      0007   000000 TRMTX     0003 R 000077 TSTAR     0000 R 004303 TSTARM    0000   004536 TUBE
0000   004426 TUBEA     0002 R 000050 TW        0010   001607 TX        0002 R 001064 TO        0005 R 000620 VELA
0000 R 004253 VELM      0005 R 000764 VELR      0006 R 000001 VERTX     0027 R 000000 VISC      0003   000135 VSC
0000 R 006020 W         0015 R 000312 WIFLD     0016 R 000000 WRAT      0013 R 000006 WWA       0013 R 000007 WWB
0000 R 004337 WWC       0000 R 004343 WWD       0000 R 004341 WWR1      0000 R 004342 WWR2      0002 R 001066 WO
0000 R 006020 W1        0000 R 006033 W2        0000 R 004375 XFNU      0002 R 000536 XIFN      0002 R 000005 XIMP
0002 R 000000 XITB      0002 R 001106 XL        0000 R 004360 XNUSLT    0002 R 001054 XRE       0013 R 000005 XSMP
0013 R 000004 XSPM      0002 R 001057 XX10      0002 R 001060 XX11      0002 R 001061 XX12      0000 R 004377 XX13
0007 R 003446 XX2       0004 R 000000 XX20      0002 R 001055 XX3       0002 R 001056 XX4       0004 R 000001 XX48
0000 R 000001 Y         0000 R 002571 YS        0000 R 003721 YSIMP     0000 R 003411 YST       0002 R 000550 ZETA
0007 R 003453 ZZ2
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```
00100      1*    C
00100      2*    C     THIS PROGRAM PROVIDES :
00100      3*    C       1- INPUT AND OUTPUT
00100      4*    C       2- UNIT CONVERSION
00100      5*    C       3- COMPUTATION OF DESIGN PARAMETERS
00100      6*    C       4- PREPARATION FOR PRINCIPLE INTEGRATION
00100      7*    C
00100      8*    C
00100      9*    C     INPUT DATA
00100     10*    C     **********
00100     11*    C
00100     12*    C     THE FOLLOWING CARDS DESCRIBE EACH VARIABLE IN THE NAMELISTS
00100     13*    C     WITH THEIR CORRESPONDING UNITS
00100     14*    C
00100     15*    C     NAMELIST /SYSTEM/
00100     16*    C       ISYM    = 0 SINGLE, FLAT, SYMMETRICAL PANEL WITH STRAIGHT TUBES
00100     17*    C               = 1 CURVED PANELS, STRAIGHT TUBES
00100     18*    C               = 2 FLAT PANELS, U-SHAPED TUBES
00100     19*    C               = 3 CURVED PANELS, U-SHAPED TUBES
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00100  C          = 4 FLAT PANELS, STRAIGHT TUBES, NON-SYMMETRICAL LOADING
00100  C    NSRD    NUMBER OF RADIATING SIDES (1 OR 2)
00100  C    NT      NUMBER OF FLAT, SYMMETRICAL PANELS, EACH WITH NTBS TUBES
00100  C    TSTAR   ARRAY OF SINK TEMPERATURES FOR CARD INPUT
00100  C
00100  C  NAMELISTS TUBEA, FINA, FLUIDA, AND MRI ARE USED ONLY FOR THE
00100  C  NON-SYMMETRICAL CASE (ISYM>0)
00100  C
00100  C  NAMELIST /TUBEA/
00100  C    D       INNER DIAMETER OF TUBE [IN]
00100  C    AL      TUBE LENGTHS FOR STRAIGHT TUBE CASE [FT]
00100  C    W1      INLET-OUTLET TUBE SPACING FOR U-SHAPE CASE [IN]
00100  C    W2      CROSSOVER TUBE SPACING FOR U-SHAPE CASE [IN]
00100  C
00100  C  NAMELIST /FINA/
00100  C    H       HALF-WIDTHS OF FINS FOR STRAIGHT TUBE CASE [IN]
00100  C    TH      FIN THICKNESSES [IN]
00100  C    ABEMF   FIN ABSORBTIVITY/EMISIVITY RATIO (USED WITH MRI INPUT)
00100  C
00100  C  NAMELIST /FLUIDA/
00100  C    TIN     ENTRANCE (AND REFERENCE) TEMPERATURES [R]
00100  C    PIN     ENTRANCE (AND REFERENCE) PRESSURES [LBF/SQ.FT]
00100  C    M       COOLANT REFERENCE MASS FLOW RATE PER PANEL [LBM/HR]
00100  C
00100  C  NAMELIST /MRI/
00100  C    ITAPE   UNIT NUMBER ATTACHED TO MRI TAPE
00100  C    ICASE   DATA CASE NUMBER ON MRI TAPE
00100  C    NTM     NUMBER OF DATA POINTS IN DATA CASE
00100  C    TO      TIME POINT IN ORBIT FROM WHICH TO TAKE DATA [MIN]
00100  C    PHIN    ANGLES OF PANELS RELATIVE TO MRI BASE DATA [DEGREES]
00100  C
00100  C  THE NAMELIST QNML IS USED ONLY IN THE SYMMETRICAL CASE (ISYM=0)
00100  C
00100  C  NAMELIST /QNML/
00100  C    ITAPE   UNIT NUMBER ATTACHED TO MRI TAPE
00100  C    ICASE   DATA CASE NUMBER ON MRI TAPE
00100  C    NTM     NUMBER OF DATA POINTS IN DATA CASE
00100  C    TO      STEADY-STATE TIME POINT AT WHICH TO TAKE DATA [MIN]
00100  C    PHN     ANGLE OF PANEL RELATIVE TO MRI BASE DATA [DEGREES]
00100  C
00100  C  NAMELIST /TUBE/
00100  C    DITBI   TUBE INNER DIAMETER FOR SYMMETRICAL CASE [IN]
00100  C    STBI    TUBE THICKNESS [IN]
00100  C    XL      TUBE LENGTH FOR SYMMETRICAL CASE [FT]
00100  C    RHOTBI  TUBE DENSITY [LBM/CU.FT]
00100  C    MZ      NUMBER OF NODAL POINTS ALONG THE TUBE LENGTH (LESS THAN OR
00100  C            EQUAL TO 10)
00100  C    NRTBI   NUMBER OF NODAL POINTS IN THE TUBE WALL RADIAL DIRECTION
00100  C            (LESS THAN OR EQUAL TO 5)
00100  C    NTBS    NUMBER OF TUBES
00100  C
00100  C  THE NAMELIST FLOW IS USED ONLY IN THE SYMMETRICAL CASE (ISYM=0)
00100  C
00100  C  NAMELIST /FLOW/
00100  C    MDOTI   TOTAL COOLANT REFERENCE MASS FLOW RATE [LBM/HR]
00100  C    TO      ENTRANCE (AND REFERENCE) TEMPERATURE [R]
00100  C    PO      ENTRANCE (AND REFERENCE) PRESSURE [LBF/SQ.FT]
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00100   C
00100   C     NAMELIST /FIN/
00100   C       NX      NUMBER OF NODAL POINTS ALONG THE FIN HEIGHT (LESS THAN
00100   C               OR EQUAL TO 10)
00100   C       SROOTI  FIN ROOT THICHNESS FOR SYMMETRICAL CASE [IN]
00100   C       HFNI    FIN HEIGHT FOR SYMMETRICAL CASE [IN]
00100   C       STIPI   FIN TIP THICKNESS FOR SYMMETRICAL CASE [IN]
00100   C       RHOFNI  FIN DENSITY [LBM/CU.FT]
00100   C       STAGX   DISTANCE FROM THE STAGNATION POINT ON THE SHUTTLE TO THE
00100   C               CENTER OF THE RADIATOR PANEL [FT]
00100   C       VERTX   OVERALL DIMENSION OF THE RADIATOR PANEL IN THE DIRECTION
00100   C               PARALLEL TO THE ACCELERATION OF GRAVITY [FT]
00100   C
00100   C     NAMELIST /PROTLR/
00100   C       NRMP    NUMBER OF NODAL POINTS IN THE PROTECTION LAYER RADIAL
00100   C               DIRECTION (LESS THAN OR EQUAL TO 5)
00100   C       RHOMPI  PROTECTION LAYER DENSITY [LBM/CU.FT]
00100   C       VELM    METEOROID VELOCITY [FT/SEC]
00100   C       TAU     TIME THAT VULNERABLE AREA IS EXPOSED TO METEOROID
00100   C               ENVIRONMENT [DAYS]
00100   C       PROB    PROBABILITY OF NO DAMAGE CAUSED BY METEOROID IMPACTS
00100   C               [DIMENSIONLESS]
00100   C       ALPHA   EXPERIMENTAL CONSTANT THAT RELATES METEOROID FLUX AND
00100   C               MASS [GM/(DAY.SQ.FT)]
00100   C       BTA     EXPERIMENTAL CONSTANT THAT RELATES METEOROID FLUX AND MASS
00100   C               [DIMENSIONLESS]
00100   C       GAMMA   EMPIRICAL CONSTANT USED TO ADJUST PREDICTED PENETRATION
00100   C               DEPTH TO ONES OBSERVED EXPERIMENTALLY [DIMENSIOLESS]
00100   C       PHI     EMPIRICAL CONSTANT [DIMENSIONLESS]
00100   C       THETA   EMPIRICAL CONSTANT [DIMENSIONLESS]
00100   C       ATK     EMPIRICAL CONSTANT USED TO ACCOUNT FOR SPALLING ON A
00100   C               TARGET OF FINITE THICKNESS [DIMENSIONLESS]
00100   C       AN      EXPERIMENTAL CONSTANT THAT DESCRIBES PENETRATION DEPTH AS
00100   C               A FUNCTION OF ANGLE OF INCIDENCE [DIMENSIONLESS]
00100   C
00100   C     NAMELIST /MANIFD/
00100   C       AMAN    TOTAL MANIFOLD AREA PROJECTED INTO THE FIN PLANE [SQ.FT]
00100   C
00100   C
00100   C     NAMELIST /RUNOPT/
00100   C       MSTOTR  = 1 TO COMPUTE STEADY STATE CONDITIONS
00100   C               = 2 TO SIMULATE TRANSIENT SYSTEM PERFORMANCE IN THE
00100   C                   SYMMETRICAL CASE ONLY
00100   C       DTWRTE  FIXED TIME INTERVAL BETWEEN DATA PRINTOUT DURING
00100   C               INTEGRATION [HR]
00100   C       TEND    TERMINATION TIME FOR TRANSIENT PERFORMANCE CALCULATIONS
00100   C               [HR]
00100   C       ALIMIT  ABSOLUTE ERROR LIMIT PER INTEGRATION STEP [DIMENSIONLESS]
00100   C       RLIMIT  RELATIVE ERROR LIMIT PER INTEGRATION STEP [DIMENSIONLESS]
00100   C       TI      INITIAL TEMPERATURE [R]
00100   C       LIMWRT  MAXIMUM NUMBER OF DATA RECORDING DURING INTEGRATION TOWARD
00100   C               STEADY STATE, EXCLUSIVE OF INITIAL CONDITIONS RECORD AND
00100   C               STEADY STATE RECORD
00100   C       NCONV   = 0 NO AERODYNAMIC HEATING
00100   C               = 1 ASCENT
00100   C               = 2 REENTRY
00100   C       LTT     = 0 OPTICAL PROPERTIES INDEPENDENT OF TEMPERATURE
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00100   C              = 1 OPTICAL PROPERTIES DEPENDENT ON TEMPERATURE
00100   C              = 2 QRFN AND QRMP ARE BOTH EQUAL TO ZERO BUT QINCID IS
00100   C                  CALLED
00100   C     LFLD     = 1 CONSTANT FLUID INLET CONDITIONS
00100   C              = 2 VARIABLE FLUID INLET CONDITIONS
00100   C     LTS      = 0 UNIFORM INITIAL TEMPERATURE EQUAL TO TI
00100   C              = 1 INITIAL TEMPERATURE AS OBTAINED BY PREVIOUS
00100   C                  COMPUTATIONS
00100   C
00100   C   NAMELIST/GINPT/
00100   C     IT CONTAINS THE VARIABLES IN MOST OF THE PREVIOUS NAMELISTS, AND
00100   C     IN ADDITION
00100   C     MRSTRT   = 1 NEW VELOCITY AND ALTITUDE PROFILES
00100   C              = 2 NEW IRRADIATION HISTORY
00100   C              = 3 BOTH 1 AND 2
00100   C              = 4 NEW COOLANT INLET CONDITIONS
00100   C              = 5 BOTH 1 AND 4
00100   C              = 6 BOTH 2 AND 4
00100   C              = 7 ALL (1, 2, AND 4)
00100   C              = 8 ONLY NEW PARAMETERS FROM GINPT
00100   C     IF THIS THIS NAMELIST IS OMMITED, THE PROGRAM WILL TERMINATE
00100   C
00100   C
00100   C   THE FOLLOWING CARDS DESCRIBE THE INPUT VARIABLES, OTHER THAN THOSE
00100   C   IN THE NAMELISTS, WITH THEIR CORRESPONDING UNITS
00100   C
00100   C     NA       NUMBER OF ORDERED PAIRS OF ELEMENTS IN THE VELOCITY-TIME
00100   C              ARRAY FOR ASCENT PROFILES
00100   C     NR       NUMBER OF ORDERED PAIRS OF ELEMENTS IN THE ALTITUDE-TIME
00100   C              ARRAY FOR REENTRY PROFILES
00100   C
00100   C     TA       ELEMENT OF TIME ARRAY (NA VALUES), SELECTED FOR ASCENT
00100   C              VELOCITY AND ELEVATION PROFILES [SEC]
00100   C     TR       ELEMENT OF TIME ARRAY (NR VALUES), SELECTED FOR REENTRY
00100   C              VELOCITY AND ELEVATION PROFILES [SEC]
00100   C
00100   C     VELA     ELEMENTS OF VELOCITY ARRAY (NA VALUES), SELECTED FOR
00100   C              ASCENT VELOCITY PROFILE OF ORBITER [FT/SEC]
00100   C     VELR     ELEMENTS OF VELOCITY ARRAY (NR VALUES), SELECTED FOR
00100   C              REENTRY VELOCITY PROFILE OF ORBITER [FT/SEC]
00100   C     ALTA     ELEMENT OF ALTITUDE ARRAY (NA VALUES), SELECTED FOR
00100   C              ASCENT ELEVATION PROFILE OF ORBITER [FT]
00100   C     ALTR     ELEMENT OF ALTITUDE ARRAY (NR VALUES), SELECTED FOR
00100   C              REENTRY ELEVATION PROFILE OF ORBITER [FT]
00100   C
00100   C     TBM,TBMTL  TUBE MATERIAL SPECIFICATION
00100   C              (UP TO 12 ALPHANUMERIC CHARACTERS)
00100   C     FNM,FNMTL  FIN MATERIAL SPECIFICATION
00100   C              (UP TO 12 ALPHANUMERIC CHARACTERS)
00100   C     FLU,FLUID  FLUID SPECIFICATION
00100   C              (UP TO 12 ALPHANUMERIC CHARACTERS)
00100   C     PRO,PROMTL PROTECTION LAYER MATERIAL SPECIFICATION
00100   C              (UP TO 12 ALPHANUMERIC CHARACTERS)
00100   C
00100   C     TMEFLD   TIME AT WHICH FLUID INLET CONDITIONS ARE SPECIFIED [HR]
00100   C     TIFLD    INSTANTANEOUS FLUID INLET TEMPERATURE [R]
00100   C     WIFLD    INSTANTANEOUS FLUID MASS FLOW RATE [LBM/HR]
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00100   C       NFLDTA  NUMBER OF DATA POINTS DEFINING INLET CONDITIONS
00100   C               (LESS THAN OR EQUAL TO 100)
00100   C
00100   C ***********************************************************************
00100   C
00100   C       DECLARATION
00100   C
00101           PARAMETER NTP = 10
00103           PARAMETER NTP1 = NTP+1
00104           REAL MDOT,MDOTI,M
00105           EXTERNAL DERIVM,CNTLM
00106           DIMENSION Y(200),DY(200),A(200),R(200),DELY(200),PD(200),SD(200),
00106        1    YS(200),DYST(200),YST(200),YSIMP(200),HDG(6),W1(NTP1),W2(NTP1),
00106        2    W(NTP1,2)
00107           COMMON XITB(5),XIMP(5),FP(10),FW(10),FT(10),TW(10,5),TEMP(10,10),
00107        1          TMP(10,5),QRFN(10,10),QRMP(10),XIFN(10),ZETA(10),AUX2(10),
00107        2          CONFN(10,10),CONMP(10),COB(10),DOB(10)
00110           COMMON NX,MZ,NRTB,NRMP,NCTL,IFLOW,LT,LTB,LMP,LTBMZ,LTB2MZ,LL1,
00110        1         LL2,LL3,LL4,LL5,LL6,LL7,NRMP1,NRTB1,NRMP2,NEQUS,LC,MSTOTR,
00110        2         NCTM,NM1,MM1,LIMWRT,LIM,MODA,NCCZ,NCONV
00111           COMMON FRE,FR,FNU,FMACH,FPR,FRL,FRM,FFO,FOF,FZ,FRAD,DZ,DXITB,DXIMP
00111        1          ,XRE,XX3,XX4,XX10,XX11,XX12,PHIM,PHIF,TO,P0,W0,RHO0,CP0,PI
00111        2          ,DELTA,RLIMIT,RDTWRT,TREF,TINTL,TI,RTEND,FLUX,QREF,FENTH,
00111        3          FREJ,HFN,XL,CO4,DXI,FRO,FXOH,FXHW,RHOFN
00112           COMMON /ADBH/ D,AL(NTP),H(NTP1),TH(NTP),TIN(NTP),PIN(NTP),
00112        1               M(NTP),NT,TSTAR(NTP,3),VSC(NTP),CP(NTP),CONFL(NTP),
00112        2               CONFNA(NTP),EMIS(NTP),TB(NTP),HAB(NTP1),EFF(NTP,2),
00112        3               TL(NTP,2),QOUT(NTP),DTL(NTP),TOUT(NTP)
00113           COMMON/DVM/XX20,XX48
00114           COMMON/VELALT/TA(100),TR(100),ALTA(100),ALTR(100),VELA(100),
00114        1               VELR(100),NA,NR
00115           COMMON/CNV/STAGX,VERTX,IOPTN,DX,NSRAD,SMPC,ST4,COEFF
00116           COMMON /QRD/ TRMTX(30,60),EBFN(5,5),EBMP(5),XX2(5),ZZ2(5),
00116        1              MCVRD,LCT,LTT,DZMFN,
00116        2              DXX2,CSF,EXTSFN,EXTIFN,EXTSMP,EXTIMP,DXX21,SS(5,5,5)
00116        3              ,SSTT(5,5)
00117           COMMON /QIN/TM(100), QSFN(100,2), QIFN(100,2), QSTB(100,2),
00117        1             QITB(100,2), NTM, NSRD, QTO, TX
00120           COMMON /TC/ ITAPE,ICASE,TO,ABEMF,PHIN(NTP,3)
00121           COMMON /ABSRST/ALPHFN(5,5,6),ALPHMP(5,31),EMITFN(5,5),EMITMP(5),
00121        1                EXTVCT(50)
00122           COMMON /SSF/R2, T, ALPFN,R1,XSPM,XSMP,WWA,WWB
00123           COMMON /GEOM/ SFN(10),NTBS,TNXL,TBMASS,PLMASS,FLMASS,STR
00124           COMMON /FLOINL/ NFLDTA,LFLD,TMEFLD(100),TIFLD(100),WIFLD(100),
00124        1                  FLDINT
00125           COMMON /DVCMFL/ WRAT,FLUXI
00126           EQUIVALENCE (MDOT,FLUX),(ALPFN,CTA),(W(1,1),W1(1)),(W(1,2),W2(1))
00126   C
00127           NAMELIST /SYSTEM/ ISYM,NSRD,NT,TSTAR
00130           NAMELIST /TUBEA/ D,AL,W1,W2
00131           NAMELIST /FINA/ H,TH,ABEMF
00132           NAMELIST /FLUIDA/ TIN,PIN,M
00133           NAMELIST /MRI/ ITAPE,ICASE,NTM,TO,PHIN
00134           NAMELIST /QNML/ ITAPE,ICASE,NTM,TO,PHN
00135           NAMELIST/TUBE/ DITBI,STBI,XL,RHOTBI,MZ,NRTBI,NTBS
00136           NAMELIST/FLOW/MDOTI,TO,P0
00137           NAMELIST/FIN/NX,SROOTI,HFNI,STIPI,RHOFNI,STAGX,VERTX
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00140           NAMELIST/PROTLR/NRMP,RHOMPI,RHOMET,VELM,TAU,PROB,ALPHA,BTA,GAMMA,
00140          1           PHI,THETA,ATK,AN
00141           NAMELIST/MANIFD/ AMAN
00142           NAMELIST/RUNOPT/MSTOTR,DTWRTE,TEND,ALIMIT,RLIMIT,TI,LIMWRT,NCONV,
00142          1            LTT,LFLD,LTS
00143           NAMELIST/GINPT/DITBI,STBI,XL,RHOTBI,MZ,NRTBI,NTBS,MDOTI,TO,PO,NX,
00143          1         SROOTI,HFNI,STIPI,RHOFNI,NRMP,RHOMPI,RHOMET,VELM,TAU,
00143          2         PROB,ALPHA,BTA,GAMMA,PHI,THETA,ATK,AN,AMAN,MSTOTR,
00143          3         DTWRTE,TEND,ALIMIT,RLIMIT,TI,LIMWRT,NCONV,STAGX,VERTX,
00143          4         LTT,MRSTRT,NSRD,ITAPE,ICASE,NTM,TO,PHN
00143     C
00143     C
00144       155 FORMAT(1H1,//,59X,A6,' SURFACE',/,54X,I2,1X,A6,A2,'-TUBE PANELS',
00144          1    /,58X,I1,' RADIATING ',A5,/)
00145       255 FORMAT(//,' MRI TAPE PARAMETERS:',7X,'UNIT',I3,4X,' CASE',
00145          1    I3,3X,I4,' DATA POINTS',3X,F8.3,' MINUTES INTO ORBIT',//,
00145          2    ' FIN ABSORBTIVITY/EMISSIVITY RATIO:',F8.4)
00146       355 FORMAT(/,' FIN ANGLES RELATIVE TO MRI TAPE DATA (DEGREES)',
00146          1    /,10(2X,1PE10.4))
00147       455 FORMAT(/,' FIN ANGLES AT OUTLET TUBES (MRI RELATIVE DEGREES)',
00147          1    /,10(2X,1PE10.4))
00150       555 FORMAT(//,' TUBE SPECIFICATIONS',6X,1PE10.4,
00150          1    ' INCHES INSIDE DIAMETER')
00151       655 FORMAT(/,' TUBE LENGTH (FEET)',/,10(2X,1PE10.4))
00152       755 FORMAT(/,' INLET-OUTLET TUBE SPACING (INCHES)',/,11(2X,1PE10.4))
00153       855 FORMAT(/,' CROSSOVER TUBE SPACING (INCHES)',/,11(2X,1PE10.4))
00154       955 FORMAT(//,' FIN SPECIFICATIONS',//,' FIN THICKNESS (INCHES)',
00154          1    /,10(2X,1PE10.4))
00155      1055 FORMAT(/,' FIN HALF-WIDTH (INCHES)',/,11(2X,1PE10.4))
00156      1155 FORMAT(/,' SINK TEMPERATURE (DEGREES R)',/,10(2X,1PE10.4))
00157      1255 FORMAT(10(2X,1PE10.4))
00160      1355 FORMAT(//,' FLUID SPECIFICATIONS',//,
00160          1    ' INLET TEMPERATURE (DEGREES R)',/,10(2X,1PE10.4))
00161      1455 FORMAT(/,' INLET PRESSURE (LBF/SQ.FT.)',/,10(2X,1PE10.4))
00162      1555 FORMAT(/,' MASS FLOW RATE (LBM/HR)',/,10(2X,1PE10.4))
00162     C
00162     C
00163           DATA PI/3.1415927/,SIDE/'SIDE'/,HDG/' FLAT','CURVED','STRAIGHT',
00163          1    'U-SHAPED'/
00163     C
00167           MRSTRT = 15
00170           READ(5,SYSTEM)
00173           NSRD = MAX(MIN(NSRD,2-AND(ISYM,1)),1)
00174           NSRAD = NSRD
00175           IF (ISYM.NE.0) GO TO 2000
00177           NT = 1
00200           GO TO 8
00201      2000 READ(5,TUBEA)
00204           READ(5,FINA)
00207           READ(5,FLUIDA)
00212           READ(5,MRI)
00215           NTF = (NT-1)*AND(ISYM,1)+1
00216           NT1 = NT+1
00217           IF (ITAPE.LE.0) GO TO 300
00221           IF (ISYM.NE.3) GO TO 200
00223           IU = (NT+1)/2
00224           IW = NT/2+1
```

```
00225            ANGINC = (PHIN(IU,2)+PHIN(IW,2)-PHIN(IU,1)-PHIN(IW,1))/(NT-1)
00226            DO 100 I = 1,NT
00231        100 PHIN(I,3) = (PHIN(IU,1)+PHIN(IW,1)+ANGINC*(I-1))/2
00233        200 CALL TCALC(NTF)
00234        300 IF (NTF.EQ.NT) GO TO 500
00236            DO 400 J = 1,NSRD
00241            DO 400 I = 2,NT
00244        400 TSTAR(I,J) = TSTAR(1,J)
00247        500 IF (ISYM.NE.3.OR.ITAPE.LE.0) GO TO 800
00251            PHN = (PHIN(IU,3)+PHIN(IW,3))/2
00252            TSTARM = 0
00253            DO 600 I = 1,NT
00256            PHIN(I,3) = PHN
00257        600 TSTARM = TSTARM+TSTAR(I,3)
00261            TSTARM = TSTARM/NT
00262            DO 700 I = 1,NT
00265        700 TSTAR(I,3) = TSTARM
00267        800 IF (NSRD.EQ.2) SIDE = 'SIDES'
00271            IH1 = AND(ISYM,1)+1
00272            IH2 = AND(ISYM,2)+3
00273            WRITE(6,155) HDG(IH1),NT,HDG(IH2),HDG(IH2+1),NSRD,SIDE
00303            IF (ITAPE.GT.0) WRITE(6,255) ITAPE,ICASE,NTM,TO,ABEMF
00313            IF (ITAPE.GT.0) WRITE(6,355) (PHIN(I,1),I=1,NTF)
00322            IF (ISYM.EQ.3.AND.ITAPE.GT.0) WRITE(6,455) (PHIN(I,2),I=1,NTF)
00331            WRITE(6,555) D
00334            IF (AND(ISYM,2).EQ.0) WRITE(6,655) (AL(I),I=1,NT)
00343            IF (AND(ISYM,2).NE.0) WRITE(6,755) (W1(I),I=1,NT1)
00352            IF (AND(ISYM,2).NE.0) WRITE(6,855) (W2(I),I=1,NT1)
00361            WRITE(6,955) (TH(I),I=1,NT)
00367            IF (AND(ISYM,2).EQ.0) WRITE(6,1055) (H(I),I=1,NT1)
00376            WRITE(6,1155) (TSTAR(I,1),I=1,NT)
00404            IF (ISYM.EQ.3) WRITE(6,1255) (TSTAR(I,3),I=1,NT)
00413            IF (NSRD.EQ.2.OR.ISYM.EQ.3) WRITE(6,1255) (TSTAR(I,2),I=1,NT)
00422            WRITE(6,1355) (TIN(I),I=1,NT)
00430            WRITE(6,1455) (PIN(I),I=1,NT)
00436            WRITE(6,1555) (M(I),I=1,NT)
00436      C
00436      C     ASCENT AND REENTRY PROFILE SPECIFICATIONS READ IN
00436      C
00444          8 IF (AND(MRSTRT,1).EQ.0) GO TO 12
00446            READ(5,2) NA,NR
00452          2 FORMAT (2I10)
00453            READ (5,3) (TA(I), I = 1,NA)
00461            READ (5,3) (TR(I), I = 1,NR)
00467          3 FORMAT (10F8.3)
00470            READ (5,4) (VELA(I),I=1,NA)
00476            READ (5,4) (VELR(I),I=1,NR)
00504            READ (5,4) (ALTA(I),I=1,NA)
00512            READ (5,4) (ALTR(I),I=1,NR)
00520          4 FORMAT ( 8E10.1)
00520      C
00521         12 IF (AND(MRSTRT,2).EQ.0) GO TO 24
00523            IF (MRSTRT+ISYM.EQ.15) READ(5,GNML)
00527            IF (ITAPE.GT.0) GO TO 24
00531            PHN = 0.0
00532            ICASE = 0
00533            NS = 6
```

```
00534          DO 20 J = 1,NSRD
00537          IU = J+2
00540          K1 = J*3-2
00541          K2 = K1+2
00542          DO 14 I = 1,NTM
00545          READ(5,3) TM(1),(QSFN(K,1),K=K1,K2),(QIFN(K,1),K=K1,K2),
00545         1          (QSTB(K,1),K=K1,K2)
00564          IF (J.EQ.2) READ(3) NS,TM(1),(QSFN(K,1),QIFN(K,1),QSTB(K,1),K=1,3)
00577       14 WRITE(IU) NS,TM(1),(QSFN(K,1),QIFN(K,1),QSTB(K,1),K=1,6)
00612       20 CALL CLOSE(J+2,1)
00612    C
00612    C     MATERIAL SPECIFICATIONS READ IN
00614       24 IF (MRSTRT.NE.15) GO TO 28
00616          READ(5,16) TBM,TBMTL,FNM,FNMTL,FLU,FLUID,PRO,PROMTL
00616    C
00616    C     SYSTEM SPECIFICATIONS READ IN
00616    C
00630       15 READ(5,TUBE)
00633          IF (ISYM.EQ.0) READ(5,FLOW)
00637          READ(5,FIN)
00642          READ(5,PROTLR)
00645          READ(5,MANIFD)
00645    C
00645    C     PROGRAM CONTROL PARAMETERS READ IN
00645    C
00650          READ(5,RUNOPT)
00653       16 FORMAT(2A6)
00653    C
00653    C     FLUID INLET CONDITIONS READ IN
00653    C
00654          IF (LFLD .EQ. 1) GO TO 30
00656       28 IF (AND(MRSTRT,4).EQ.0) GO TO 30
00660          READ(5,2) NFLDTA
00663          READ (5,22) (TMEFLD(I),TIFLD(I),WIFLD(I),I=1,NFLDTA)
00673       22 FORMAT (3F20.6)
00673    C
00674       30 IUL = AND(ISYM,2)+1
00675          DO 840 I = 1,NT
00700      840 M(I) = M(I)/(32.174*NTBS)
00702          DO 9997 IU = 1,IUL
00705          IF (AND(ISYM,2).EQ.0) GO TO 2100
00707          IW = AND(IU,1)
00710          H(1) = W(1,2-IW)
00711          H(NT+1) = MIN(W1(NT+1),W2(NT+1))
00712          IF (NT.EQ.1) GO TO 1100
00714          DO 1000 IT = 2,NT
00717     1000 H(IT) = W(1,2-IW)/2
00721     1100 DO 1300 IT = 1,NT
00724          AL(IT) = 0
00725          I1 = IT+1
00726          DO 1200 I = I1,NT1
00731     1200 AL(IT) = W(1,1+IW)+AL(IT)
00733     1300 AL(IT) = (2-AND(IU,1))*AL(IT)/12
00735     2100 IF (ISYM.GT.0) CALL ADIABH(BOOL(AND(ISYM,3).EQ.3)*MOD(4-IU,3)+1)
00737          DO 9997 IT = 1,NT
00742          IF (ISYM.EQ.0) GO TO 34
00744          MSTOTR = 1
```

```
00745        IF (ITAPE.GT.0) PHN = PHIN(IT,IU)
00747        DITBI = D
00750        XL = AL(IT)
00751        MDOTI = M(IT)*32.174*NTBS
00752        T0 = TIN(IT)
00753        TIN(IT) = TOUT(IT)
00754        P0 = PIN(IT)
00755        SROOTI = TH(IT)
00756        STIPI = TH(IT)
00757        HFNI = (HAB(IT)*EFF(IT,1)+(2*H(IT+1)-HAB(IT+1))*EFF(IT,2))/
00757       1    (EFF(IT,1)+EFF(IT,2))-D/2-STBI
00760     34 IF (AND(MRSTRT,2).NE.0) CALL QINCID (MSTOTR,PHN)
00760  C     LISTING OF SYSTEM SPECIFICATIONS AND CONTROL PARAMETERS
00760  C
00762        WRITE(6,9998)
00764        WRITE(6,QNML)
00767        WRITE(6,TUBE)
00772        WRITE(6,FLOW)
00775        WRITE(6,FIN)
01000        WRITE(6,PROTLR)
01003        WRITE(6,MANIFD)
01006        WRITE(6,RUNOPT)
01006  C
01006  C     UNIT CONVERSION ON INPUT DATA
01006  C
01011        DITB     = DITBI/12.0
01012        STB      = STBI /12.0
01013        SROOT    = SROOTI/12.0
01014        STIP     = STIPI/12.0
01015        HFN      = HFNI /12.0
01016        RITB     = DITB/2.0
01017        MDOT     = MDOTI/32.174
01020        ROTB     = (RITB+STB)*12.0
01021        RHOTB    = RHOTBI/32.174
01022        RHOFN    = RHOFNI/32.174
01023        RHOMP    = RHOMPI/32.174
01023  C
01024        TNN      = FLOAT(NTBS)
01024  C
01024  C     METEOROID PROTECTION LAYER THICKNESS
01024  C
01025        SMPC     = TK(GAMMA,ATK,BTA,RHOMET,THETA,PHI,AN,ALPHA,VELM,PROB,
01025       1          TAU,RHOMPI,XL,TNN,AMAN,T0,ROTB)
01026        SMP      = SMPC/12.0
01026  C
01026  C     INTERSECTION BETWEEN OUTER TUBE CIRCLE AND UPPER FIN PLANE
01026  C
01027        WWA      = (STIP-SROOT)/(2.0*HFN)
01030        WWC      = WWA**2+1.0
01031        SRO2     = SROOT/2.0
01032        WWR1     = RITB+STB
01033        WWR2     = WWR1+SMP
01034        WWB      = SRO2-WWA*WWR1
01035        WWD      = SQRT(WWC*WWR2**2-WWB**2)
01036        XSMP     = ((-WWA*WWB+WWD)/WWC-WWR1)/HFN
01036  C
01036  C     CONTROL INTEGERS
```

```
01036          C
01037               NRTB    = NRTBI
01040               NM1     = NX-1
01041               MM1     = MZ-1
01042               NRMP1   = NRMP-1
01043               NRMP2   = NRMP-2
01044               NRTB1   = NRTB-1
01045               LT      = MZ*NM1
01046               LTB     = LT+MZ
01047               LMP     = LTB+MZ*NRTB
01050               LTBMZ   = LTB+MZ
01051               LTB2MZ  = LTBMZ+MZ
01052               LL1     = LTB+(NRTB-2)*MZ
01053               LL2     = LL1-MZ
01054               LL3     = LMP+MZ
01055               LL4     = LL1+MZ
01056               LL5     = LMP+NRMP2*MZ
01057               LL6     = LL5-MZ
01060               LL7     = LL6-MZ
01061               LC      = MZ/2
01062               IF(NCONV.EQ.1) IOPTN = 0
01064               IF(NCONV.EQ.2) IOPTN = 1
01064          C
01064          C    GRID INTERVALS
01064          C
01066               DZ      = 1.0/FLOAT(MM1)
01067               DXI     = 1.0/FLOAT(NM1)
01070               DXITB   = STB/(RITB*FLOAT(NRTB1))
01071               DXIFN   = HFN/RITB*DXI
01072               DXIMP   = SMP/(RITB*FLOAT(NRMP1))
01073               DELTA   = DITB/XL
01073          C
01073          C    GRID SPACINGS
01073          C
01074               XITB(1) = 1.0
01075               DO 50 I = 2,NRTB
01100            50 XITB(I) = XITB(I-1)+DXITB
01102               XIMP(1) = XITB(NRTB)
01103               DO 55 I = 2,NRMP
01106            55 XIMP(I) = XIMP(I-1)+DXIMP
01110               ZETA(1) = 0.0
01111               DO 60 J = 2,MZ
01114            60 ZETA(J) = ZETA(J-1)+DZ
01116               XIFN(1) = 0.0
01117               DO 65 J = 2,NX
01122            65 XIFN(J) = XIFN(J-1)+DXI
01122          C
01124               MMEP    = (INT(2.0*XSMP/DXI)+1)/2
01125               MCVRD   = MMEP
01126               IF(XSMP.GE.XIFN(MMEP+1)) MMEP = MMEP+1
01126          C
01130               DXX2    = (1.0-XSMP)/4.5
01131               DXX21   = 2.0
01132               XX2(1)  = XSMP+DXX2/2.0
01133               XSPM    = ((0.5+FLOAT(MCVRD))*DXI-XSMP)/DXI
01134               IF(MCVRD.EQ.0) XSPM = (DXI-2.0*XSMP)/DXI
01136               ZZ2(1)  = 0.0
```

```
01137                DO 66 I = 2,5
01142                ZZ2(I)  =  ZZ2(I-1)+0.25
01143             66 XX2(I)  = XX2(I-1)+DXX2
01143          C
01143          C     GENERAL CONSTANTS
01143          C
01145                TOL      = SROOT/(2.0*HFN)
01146                CTA      = TOL-STIP/(2.0*HFN)
01147                DTA      = SQRT(1.0+CTA**2)
01150                DO 70 I=2,NM1
01153                BOL      = TOL-CTA*XIFN(I)
01154                DOB(I)   = DTA/(2.0*BOL)
01155             70 COB(I)   = CTA/BOL
01155          C
01157                SLOPE    = (SROOT-STIP)/(2.0*HFN)
01160                SFN(1)   = SROOT
01161                SFN(NX)  = STIP
01162                DO 80 I  = 2,NM1
01165             80 SFN(I)   = STIP+2.0*HFN*SLOPE*(1.0-XIFN(I))
01165          C
01165          C
01167                RHOO     = RHOF(PO,TO)
01170                RHOI     = RHOF(PO,TI)
01171                XRE      = 2.0*MDOT/(PI*TNN*RITB)
01172                FRL      = (DELTA/2.0)**2
01173                FFO      = 4.0/(XRE*DELTA)*RHOO/RHOTB
01174                FOF      = FFO*RHOTB/RHOMP
01175                REY      = XRE/VISC(RHOI,TI)
01176                FRE      = RHOO*DELTA/XRE
01177                FRM      = ((RITB+STB)/XL)**2
01200                FRD      = 1.714E-09*TO**3
01201                FRAD     = FRD*RITB
01202                FRD      = FRD*HFN
01203                PRLNTL   = (VISC(RHOI,TI)*CPF(RHOI,TI))/THCF(RHOI,TI)
01204                QREF     = FRD*TO*TNN*2.0
01205                AITB     = TNN*PI*RITB**2
01206                W0       = XRE/(DITB*3600.0*RHOO)
01207                CPO      = CPF(RHOO,TO)
01210                HFLO     = HFL(RHOO,TO)
01211                FENTH    = FLUX*(HFLO+W0**2/1556.36)
01212                FREJ     = PI*TO
01213                FXOH     = (HFN/XL)**2
01214                FXHW     = XL/(W0*3600.0*HFN**2)
01214          C
01215                T        = SRO2/HFN
01216                R1       = WWR1/HFN
01217                R2       = WWR2/HFN
01220                DZMFN    = XL/(HFN*4.0)
01220          C
01221                TREF     = XL*DITB/XRE*RHOO
01222                RDTWRT   = DTWRTE/TREF
01223                RTEND    = TEND/TREF
01224                STR      = TO*HFN*(SROOT+STIP)*TNN*SQRT(RHOFN/(PI*TREF))
01224          C
01225                XX3      = DXITB/DXIMP
01226                XX4      = DXITB/DXIFN
01227                XX10     = 1.0/(4.0*XIMP(NRMP)-DXIMP)
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01230            XX11    = 4.0*XX10*(2.0*XIMP(NRMP)-DXIMP)/(DXIMP**2)
01231            XX12    = 8.0*XX10*XIMP(NRMP)/DXIMP
01231       C
01232            PHIF    = 4.0*ASIN(SROOT/(2.0*WWR1+SMP))
01233            PHIM    = 2.0*PI-4.0*ASIN(SROOT/(2.0*WWR2))
01234            PHIF    = PHIF*RITB/HFN
01235            COM     = PHIM*WWR2/(2.0*HFN)
01235       C
01235       C
01236            COEFF  =  3600./STAGX
01237            ST4     = 0.1714E-08*T0**4.0
01240            QT0     = ST4
01241            DX      =  HFN*DXI*12.0
01241       C
01241       C    INITIAL TEMPERATURE PROFILES
01241       C
01242            IF (MRSTRT-LTS*8.LE.0) GO TO 312
01244            TINTL    = TI/T0
01245            DO 310 J=1,MZ
01250            DO 302 I=1,NRTB
01253        302 TW(J,I) = TINTL
01255            DO 305 I=1,NRMP
01260        305 TMP(J,I)= TINTL
01262            CONMP(J)    = 0.0
01263            DO 310 I=1,NX
01266            CONFN(J,I) = 0.0
01267        310 TEMP(J,I) = TINTL
01267       C
01267       C    INITIAL FLOW CONDITIONS
01267       C
01272        312 IFLOW    = 1
01273            FT(1)    = TW(1,1)
01274            IF (LFLD .EQ. 2) FT(1) = TIFLD(1)/T0
01276            WRAT     = 1.0
01277            FLUXI = MDOTI
01300            IF (LFLD .EQ. 2) WRAT = WIFLD(1)/FLUXI
01302            CALL FLSTRT(REY,PRLNTL,DELTA)
01302       C
01302       C    CRITERIA FOR LUMPED-PARAMETER TREATMENT OF TUBE PLUS
01302       C    PROTECTION LAYER
01302       C
01303            TAVG     = 0.5*(TI+T0)
01304            XNUSLT   = FNU*DELTA*REY*PRLNTL/4.0
01305            BIOTNO   = XNUSLT/DITB*THCF(RHO0,T0)*(STB/THCTB(TAVG)+SMP/THCMP
01305           1           (TAVG))
01306            WRITE(6,313) XNUSLT,BIOTNO
01312        313 FORMAT(1H ,5X,25HINIT. NUSSELT NO. NU  =  ,E20.6,/,
01312           1            6X,25HWALL BIOT NO.      BI  =  ,E20.6,/)
01313            IF(BIOTNO.GT.0.05) GO TO 314
01315            NRTB     = 0
01316            LL4      = MZ*NX
01317            LL5      = LL4
01320            LL6      = MZ-2
01321            LTB      = LL4
01322            NEQUS    = MZ*(NX+1)
01322       C
01322       C
```

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01322      C     MASS CALCULATIONS
01322      C
01323       314 DO 315 J=1,MZ
01326       315 Y(J)     = 1.0/FW(J)
01330           TNXL     = TNN*XL
01331           FLMASS   = TNXL*AITB*RHOO*DEFINT(Y,DZ,MZ)
01332           FNMASS   = TNXL*HFN*RHOFN*(SROOT+STIP)
01333           TBMASS   = TNXL*PI*STB*(DITB+STB)*RHOTB
01334           PLMASS   = TNXL*SMP*RHOMP*(DITB+2.0*STB+SMP)*PHIM/2.0
01335           TOTMSS   = FLMASS+FNMASS+PLMASS+TBMASS
01336           FLMASI   = FLMASS*32.174
01337           FNMASI   = FNMASS*32.174
01340           TBMASI   = TBMASS*32.174
01341           PLMASI   = PLMASS*32.174
01342           TOTMSI   = TOTMSS*32.174
01342      C
01343           ATOT     = TNXL*(2.0*(HFN+STB)+DITB)
01344           WRITE(6,320) XL,DITBI,STBI,TBM,TBMTL,TBMASI,NTBS,
01344          1              HFNI,SROOTI,STIPI,FNM,FNMTL,FNMASI,NSRAD,
01344          2              FLU,FLUID,FLMASI
01367           WRITE (6,321) SMPC,PLMASI,PRO,PROMTL,
01367          1              TOTMSI,ATOT
01377       320 FORMAT(1H0,15X,17HSYSTEM PARAMETERS,/,16X,17H*****************,//,
01377          2 6X,35HTUBE LENGTH ,                  XL = ,F10.3,11H FT         ,/,
01377          3 6X,35H     INTERNAL DIAMETER ,    DITB = ,F10.3,11H IN         ,/,
01377          4 6X,35H     WALL THICKNESS ,        STB = ,F10.3,11H IN         ,/,
01377          5 6X,35H     MATERIAL                      ,2A6                  ,/,
01377          6 6X,35H     MASS   (ALL TUBES) ,    MTB = ,F10.4,11H LBM        ,/,
01377          1 6X,35H     NUMBER OF TUBES,       NTBS = ,I10                  ,//
01377          7 6X,35HFIN  HEIGHT ,                HFN = ,F10.3,11H IN         ,/,
01377          8 6X,35H     THICKNESS AT ROOT ,   SROOT = ,F10.3,11H IN         ,/,
01377          9 6X,35H     THICKNESS AT TIP ,     STIP = ,F10.3,11H IN         ,/,
01377          1 6X,35H     MATERIAL                      ,2A6                  ,/,
01377          2 6X,35H     MASS (ALL FINS) ,       MFN = ,F10.4,11H LBM        ,/,
01377          3 6X,35H     NO. OF FIN SIDES RADIATING  = ,I10                  ,//
01377          3 6X,35HCOOLANT FLUID IS                   ,2A6                  ,/,
01377          3 6X,35H     MASS (IN ALL TUBES) ,   MFL = ,F10.4,11H LBM        ,/)
01400       321 FORMAT (1H0,6X,35HPROTECTION LAYER THICKNESS,  SMP = ,F10.3,11H IN
01400          1          ,/,
01400          6 6X,35H     MASS,                   MMP = ,F10.3,11H LBM        ,/,
01400          7 6X,35H     MATERIAL IS                   ,2A6                  ,//
01400          8 6X,35HTOTAL MASS (EXCL. MANIFLD.) MTOT = ,F10.4,11H LBM        ,/,
01400          9 6X,39HTOTAL AREA (SINGLE NORMAL PROJECTION) ,,/,
01400          1 6X,35H                            ATOT = ,F10.4,11H SQ FT      ,/)
01400      C
01400      C      INITIALIZATION
01400      C
01400      C
01400      C      TUBE
01400      C
01401            IF(NRTB.EQ.0) GO TO 341
01401      C
01403            PFLD     = PO*FP(LC)
01404            TFLD     = TO*FT(LC)
01405            RHOFLD   = RHOF(PFLD,TFLD)
01406            XFNU     = THCF(RHOFLD,TFLD)/(4.0*THCTB(TINTL))*FNU*REY*PRLNTL
01406           1              *DELTA*DXITB
```

```
01407                DO 330 J=1,MZ
01412                DO 325 I=2,NRTB1
01415                K         = LTB+MZ*(I-1)+J
01416            325 Y(K)      = TW(J,I)
01420                LTBJ      = LTB+J
01421            330 Y(LTBJ) = (XFNU*FT(J)+4.0*TW(J,2)-TW(J,3))/(XFNU+3.0)
01421          C
01421          C     PROTECTION LAYER
01421          C
01421          C
01423                DO 340 J=1,MZ
01426                DO 335 I=2,NRMP1
01431                K         = LMP+MZ*(I-2)+J
01432            335 Y(K)      = TMP(J,I)
01434                Y(LL4+J)= TMP(J,1)
01435            340 Y(LL5+J)= TMP(J,NRMP)
01435          C
01435          C     FIN
01435          C
01437            341 DO 350 I=2,NX
01437          C
01442                DO 350 J=1,MZ
01445                K         = MZ*(I-2)+J
01446            350 Y(K)      = TEMP(J,I)
01446          C
01446          C     FLUID
01446          C
01451                DO 360 J=1,MZ
01454            360 Y(LT+J) = FT(J)
01454          C
01456                IF(NRTB.NE.0) GO TO 364
01460                DO 361 J=1,MZ
01463                K         = LL4+J
01464            361 Y(K)      = TW(J,1)
01464          C
01466                XX3       = (2.0-PHIM/PI)*(RITB+STB+SMP)
01467                XX4       = 2.0*(SROOT-DXI/2.0*(SROOT-STIP))/(PI*HFN)
01470                XX10      = RHOTB*STB*(DITB+STB)/TREF
01471                XX11      = RHOMP*SMP*(DITB+2.0*STB+SMP)*PHIM/(2.0*PI*TREF)
01472                XX12      = RHOFN*DXI*HFN/PI*(SROOT-DXI/4.0*(SROOT-STIP))/TREF
01473                XX13      = PHIM*(RITB+STB+SMP)
01474                XX20      = DXI*HFN/XX13
01475                XX48      = DXI*12.0
01476                FRAD      = FRD*XX13/(HFN*PI)
01476          C
01477            364 DO 365 I=1,NEQU5
01502                A(I)      = ALIMIT
01503            365 R(I)      = RLIMIT
01505                RLIMIT    = RLIMIT*5.0
01505          C
01505          C
01506                IF (OR(MRSTRT,2-LTT).GT.8) CALL SHAPEF
01506          C
01506          C
01506          C
01510                TIME      = 0.0
01511                DTME      = 0.001
```

```
01511          C
01512                LCT     = 1
01513                NCTM    = 0
01514                LIM     = 0
01515                MODA    = 0
01516                NCCZ    = 0
01516          C
01517                NTRY    = 1
01520                IFVD    = 0
01521                IBKP    = 1
01522                IERR    = 0
01522          C
01522          C     PRINCIPLE INTEGRATION
01522          C
01523                CALL RKS(DERIVM,CNTLM,Y,DY,A,R,TIME,DTME,NEQUS,IFVD,IBKP,NTRY,IERR
01523               1         ,DELY,PD,SD,YS,YST,DYST,YSIMP)
01524           9997 RLIMIT  = R(1)
01527                IF (ISYM.NE.0) GO TO 9999
01531                READ (5,GINPT, END = 9999)
01534                MRSTRT = AND(MRSTRT,7)
01535                GO TO 8
01536           9998 FORMAT(1H1)
01537           9999 STOP
01540                END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  MTXINV  ******
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```
QFOR,S ME*NASA5.MTXINV,ME*NASA5.MTXINV
FOR S9A-07/13/72-20:57:03 (0,)

   SUBROUTINE MTXINV    ENTRY POINT 000166

   STORAGE USED: CODE(1) 000206; DATA(0) 000037; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003   QRD    003670

   EXTERNAL REFERENCES (BLOCK, NAME)

    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000016 105G      0001     000076 11L       0001     000031 111G      0001     000052 121G      0001     000055 125G
    0001     000117 136G      0001     000122 142G      0001     000137 20L       0000 R   000001 AA        0000 R   000005 B
    0003     003465 CSF       0003     003464 DXX2      0003     003472 DXX21     0003     003463 DZMFN     0003     003410 EBFN
    0003     003441 EBMP      0003     003467 EXTIFN    0003     003471 EXTIMP    0003     003466 EXTSFN    0003     003470 EXTSMP
    0000 I   000000 I         0000     000011 INJP$     0000 I   000003 I1        0000 I   000006 I2        0000 I   000002 J
    0000 I   000004 K         0003     003461 LCT       0003     003462 LTT       0003     003460 MCVRD     0003     003473 SS
    0003 R   000000 TRMTX     0003     003446 XX2       0003     003453 ZZ2


00101              SUBROUTINE MTXINV(N,M)
00101        C
00101        C   THIS SUBROUTINE SOLVES A SYSTEM OF LINEAR ALGEBRIC EQUATIONS BY
00101        C   MATRIX INVERSION
00101        C
00103              COMMON /QRD/ TRMTX(30,60),EBFN(5,5),EBMP(5),XX2(5),ZZ2(5),
00103             1             MCVRD,LCT,LTT,DZMFN,
00103             2             DXX2,CSF,EXTSFN,EXTIFN,EXTSMP,EXTIMP,DXX21,SS(5,5,5)
00104              DO 20 I    =1,N
00107              AA         =TRMTX(I,I)
00110              DO 9 J     =1,M
00113            9 TRMTX(I,J)=TRMTX(I,J)/AA
00115              IF (I.EQ.1) GO TO 11
00117              I1         = I-1
00120              DO 10 K    =1,I1
00123              B          =TRMTX(K,I)
00124              DO 10 J    =1,M
00127           10 TRMTX(K,J)=TRMTX(K,J) -TRMTX(I,J) * B
00132              IF (I.EQ.N) GO TO 20
00134           11 I2         = I+1
00135              DO 15 K    =I2,N
00140              B          =TRMTX(K,I)
00141              DO 15 J    =1,M
00144           15 TRMTX(K,J)=TRMTX(K,J) -TRMTX(I,J) * B
00147           20 CONTINUE
```

```
00151     26*           RETURN
00152     27*           END
        END OF COMPILATION:        NO  DIAGNOSTICS.

@HDG,P  ******  NUS  ******
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@FOR,S ME*NASA5.NUS,ME*NASA5.NUS
FOR S9A-07/13/72-20:57:08 (0,)

   SUBROUTINE NUS       ENTRY POINT 000573

   STORAGE USED: CODE(1) 000642; DATA(0) 000114; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   YINT
    0004   NEXP6$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000550 100L      0001     000354 150G      0001     000374 161G      0001     000407 166G      0001     000443 175G
    0001     000243 20L       0001     000456 202G      0001     000513 211G      0001     000526 216G      0001     000324 30L
    0001     000431 40L       0001     000501 50L       0000 R 000015 BETA       0000 R 000021 FORCE      0000 R 000020 FREE
    0000 R 000017 GP          0000 R 000016 GRASH      0000 I 000023 I          0000     000066 INJP$     0000 R 000000 MACH
    0000 R 000004 NUS         0000 R 000010 REY        0000 R 000014 REYNO      0000 R 000022 X          0003 R 000000 YINT


00101               SUBROUTINE NUS(MACHNO,TATM,CATM,TIN,PRATM,VISATM,RHOATM,
00101             1          STAGX,VERTX,NSRAD,NUS1)
00101         C
00101         C   THIS SUBROUTINE COMPUTES :
00101         C     A SINGLE NUSSELT NUMBER FOR THE CALCULATION OF THE AERODYNAMIC
00101         C     HEATING OF THE ORBITER RADIATOR SYSTEM AT THE CURRENT TIME
00101         C
00103               REAL MACHNO,NUS1,MACH(4),NUS(4)
00104               DIMENSION REY(4)
00105               REYNO    =  MACHNO*STAGX*CATM*RHOATM/VISATM
00106               IF (MACHNO .GT. 1.0)  GO TO 20
00110               IF (MACHNO .LE. 1.0 .AND. MACHNO .GE. 0.5)  GO TO 30
00110         C
00110         C FREE CONVECTION NUSSELT NUMBER
00110         C
00112               BETA     =  2.0/(TIN+TATM)
00113               GRASH    =  32.174*BETA*(RHOATM/VISATM)**2*VERTX**3.*(TIN-TATM)
00114               GP       =  GRASH*PRATM
00115               IF (GP .GT. 1.0E-01 .AND. GP .LE. 1.0E+04)  FREE  =  1.585*(GP)
00115             1                **0.195
00117               IF (GP .GT. 1.0E+04 .AND. GP .LE. 1.0E+09)  FREE  =  0.59*(GP)**
00117             1         0.25
00121               IF (GP .GT. 1.0E+09)  FREE  =  0.13*(GP)**0.33333
00121         C
00121         C LOW SPEED NUSSELT NUMBERS FOR LAMINAR, TURBULENT AND TRANSITION FLOWS
00121         C
00123               IF (REYNO .LT. 1.0E+05)
00123             1 FORCE  =  0.332*REYNO**0.5*PRATM**0.33333
00125               IF (REYNO .GT. 1.0E+06)
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00125          1 FORCE  =  0.0288*REYNO**0.8*PRATM**0.33333
00127            IF (REYNO .LE. 1.0E+06 .AND. REYNO .GE. 1.0E+05)
00127          1 FORCE  =  6.78E-05*PRATM**0.33333*REYNO**1.238
00131            NUS1   =  FREE*STAGX/VERTX+FORCE
00132            GO TO 100
00132      C
00132      C HIGH SPEED NUSSELT NUMBERS FOR LAMINAR, TURBULENT AND TRANSITION FLOWS
00132      C
00133        20 IF (REYNO .LT. 1.0E+05)
00133          1 NUS1   =  0.3751*PRATM*REYNO**0.5014
00135            IF (REYNO .GT. 1.0E+06)
00135          1 NUS1   =  0.0346*PRATM*REYNO**0.7746
00137            IF (REYNO .LE. 1.0E+06 .AND. REYNO .GE. 1.0E+05)
00137          1 NUS1   =  3.339E-04*PRATM*REYNO**1.1111
00141            GO TO 100
00141      C
00141      C LAMINAR, TRANSITION AND TURBULENT NUSSELT NUMBERS FOR FLOWS THAT LIE
00141      C BETWEEN LOW AND HIGH SPEED MODELS
00141      C
00142        30 MACH(1)  =  0.4000
00143           MACH(2)  =  0.6333
00144           MACH(3)  =  0.8666
00145           MACH(4)  =  1.1000
00146           X        =  STAGX*CATM*RHOATM/VISATM
00147           DO 34 I = 1,4
00152        34 REY(I)   =  MACH(I)*X
00154           IF (REYNO .GT. 1.0E+06)  GO TO 40
00156           IF (REYNO .LT. 1.0E+05)  GO TO 50
00160           DO 36 I = 3,4
00163        36 NUS(I)  =  3.339E-04*PRATM*REY(I)**1.1111
00165           DO 38 I = 1,2
00170        38 NUS(I)  =  6.78E-05*PRATM**0.33333*REY(I)**1.238
00172           NUS1     =  YINT(MACH,NUS,4,4,MACHNO)
00173           GO TO 100
00174        40 DO 44 I = 3,4
00177        44 NUS(I)  =  0.0346*PRATM*REY(I)**0.7746
00201           DO 48 I = 1,2
00204        48 NUS(I)   =  0.0288*REY(I)**0.8*PRATM**0.33333
00206           NUS1     =  YINT(MACH,NUS,4,4,MACHNO)
00207           GO TO 100
00210        50 DO 54 I = 3,4
00213        54 NUS(I)  =  0.3751*PRATM*REY(I)**0.5014
00215           DO 58 I = 1,2
00220        58 NUS(I)   =  0.322*REY(I)**0.5*PRATM**0.33333
00222           NUS1     =  YINT(MACH,NUS,4,4,MACHNO)
00223       100 IF (NSRAD .EQ. 2) NUS1  =  2.0*NUS1
00225           RETURN
00226           END

      END OF COMPILATION:        NO  DIAGNOSTICS.


QHDG,P  ******  NUSA  ******
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****** NUSA ******                                                                          DATE 071372        PAGE      1

@FOR,S ME*NASA5.NUSA,ME*NASA5.NUSA
FOR S9A-07/13/72-20:57:12 (0,)

   FUNCTION NUSA        ENTRY POINT 000067

   STORAGE USED: CODE(1) 000103; DATA(0) 000024; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NEXP6$
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000024 2L        0001   000043 4L        0001   000057 5L        0000   000016 INJP$     0000 R 000000 NUSA
    0000 R 000001 RPD


00101      1*              FUNCTION NUSA(REY,PR,DOL)
00103      2*              REAL NUSA
00104      3*              IF(REY-2300)1,1,2
00107      4*      1       RPD=REY*PR*DOL
00110      5*              NUSA=3.65+0.0668*RPD/(1+.045*RPD**.6667)
00111      6*              GO TO 5
00112      7*      2       IF(PR-.1)3,3,4
00115      8*      3       NUSA=5+.025*(REY*PR)**.8
00116      9*              GO TO 5
00117     10*      4       NUSA=.023*(REY**.8)*(PR**.3)
00120     11*      5       RETURN
00121     12*              END
        END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  PDERIV  ******
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```
@FOR,S ME*NASA5.PDERIV,ME*NASA5.PDERIV
FOR S9A-07/13/72-20:57:13 (0,)

   FUNCTION PDERIV      ENTRY POINT 000160

   STORAGE USED: CODE(1) 000204; DATA(0) 000020; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003   ADBH   000352

   EXTERNAL REFERENCES (BLOCK, NAME)

    0004   TTIPS
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001    000036 2L       0001    000114 3L       0003    000001 AL       0003    000161 CONFL     0003    000173 CONFNA
    0003    000147 CP       0003    000000 D        0000 R  000001 DM       0003 R  000326 DTL       0003    000244 EFF
    0003    000205 EMIS     0003 R  000013 H        0003 R  000231 HAB      0000    000007 INJP$     0003 R  000064 M
    0003    000076 NT       0000 R  000000 PDERIV   0003    000052 PIN      0003    000314 QOUT      0003    000217 TB
    0003    000026 TH       0003    000040 TIN      0003 R  000270 TL       0003    000340 TOUT      0003    000077 TSTAR
    0000 R  000003 T1       0000 R  000002 T2       0003    000135 VSC


00101      1*            FUNCTION  PDERIV(J,IT,ITST)
00103      2*              PARAMETER NTP = 10
00104      3*              PARAMETER NTP1 = NTP+1
00105      4*              REAL M
00106      5*              COMMON /ADBH/ D,AL(NTP),H(NTP1),TH(NTP),TIN(NTP),PIN(NTP),
00106      6*           1  M(NTP),NT,TSTAR(NTP,3),VSC(NTP),CP(NTP),CONFL(NTP),
00106      7*           2  CONFNA(NTP),EMIS(NTP),TB(NTP),HAB(NTP1),EFF(NTP,2),TL(NTP,2),
00106      8*           3  QOUT(NTP),DTL(NTP),TOUT(NTP)
00107      9*            IF(J) ,2,3
00112     10*              CALL TTIPS(IT,ITST,1.01*HAB(IT),2*H(IT+1)-HAB(IT+1),DM,T2)
00113     11*            PDERIV=(T2-TL(IT+1,1)-DTL(IT))/(.01*HAB(IT))
00114     12*            RETURN
00115     13*      2       CALL TTIPS(IT,ITST,HAB(IT),2.0*H(IT+1)-1.01*HAB(IT+1),DM,T2)
00116     14*              CALL TTIPS(IT+1,ITST,1.01*HAB(IT+1),2*H(IT+2)-HAB(IT+2),T1,DM)
00117     15*            PDERIV=(T2-T1-DTL(IT))/(.01*HAB(IT+1))
00120     16*            RETURN
00121     17*      3       CALL TTIPS(IT+1,ITST,HAB(IT+1),2*H(IT+2)-1.01*HAB(IT+2),T1,DM)
00122     18*            PDERIV=(TL(IT,2)-T1-DTL(IT))/(.01*HAB(IT+2))
00123     19*            RETURN
00124     20*            END

       END OF COMPILATION:        NO  DIAGNOSTICS.
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QHDG,P ****** PF/CFHE ******

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****** PF/CFHE ******                                                                        DATE 071372        PAGE      1

@FOR,S ME*NASA5.PF/CFHE,ME*NASA5.PF/CFHE
FOR S9A-07/13/72-20:57:16 (0,)

   FUNCTION PF          ENTRY POINT 000047

   STORAGE USED: CODE(1) 000052; DATA(0) 000026; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000005 A        0000 R 000012 ALPHA     0000 R 000002 A1        0000 R 000003 B1        0000 R 000004 C
    0000   000017 INJP$    0000 R 000000 PF        0000 R 000001 R         0000 R 000006 RHOX      0000 R 000007 TX
    0000 R 000010 V        0000 R 000011 VM2


00101       1*              FUNCTION PF(RHO,T)
00101       2*        C
00101       3*        C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101       4*        C        PRESSURE AS A FUNCTION OF DENSITY (SLUG/CU.FT) AND
00101       5*        C             TEMPERATURE (R) OF HELIUM
00101       6*        C                                       UNITS LBF/SQ.FT
00101       7*        C
00103       8*              DATA R,A1,B1,C,A /2077.02,136.9595,3.5002295E-03,10.000658,1.49610
00103       9*             13E-02/
00111      10*              RHOX  = RHO*515.4275
00112      11*              TX    = T/1.8
00113      12*              V     = 1.0/RHOX
00114      13*              VM2   = RHOX*RHOX
00115      14*              ALPHA = C*RHOX/(TX**3)
00116      15*              PF    = (R*TX*(1.0-ALPHA)*(V+B1)-A1*(1.0-A*RHOX))*VM2*2.08846E-02
00117      16*              RETURN
00120      17*              END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  PF/CFNAK  ******
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******  PF/CFNAK  ******                                                                         DATE 071372        PAGE      1

@FOR,S ME*NASA5.PF/CFNAK,ME*NASA5.PF/CFNAK
FOR S9A-07/13/72-20:57:18 (0,)

   FUNCTION PF          ENTRY POINT 000030

   STORAGE USED: CODE(1) 000040; DATA(0) 000015; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   CAPPA
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000004 C         0003 R 000000 CAPPA      0000   000010 INJP$      0000 R 000000 PF        0000 R 000003 P0
    0000 R 000005 TK        0000 R 000001 X1         0000 R 000002 X2


00101            FUNCTION PF(RHO,T)
00101      C
00101      C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101      C        PRESSURE AS A FUNCTION OF DENSITY (SLUG/CU.FT) AND
00101      C             TEMPERATURE (R) OF NAK 78.6
00101      C                                          UNITS LBF/SQ.FT
00101      C
00103            DATA X1,X2 /58.773064,-0.008433/,P0 /2116.224/
00107            C  = (X1+X2*T)/32.174
00110            TK   = CAPPA(RHO,T)
00111            PF = (RHO/C-1.0)/TK+P0
00112            RETURN
00113            END
      END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  PF/CFSIL  ******
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@FOR,S ME*NASA5.PF/CFSIL,ME*NASA5.PF/CFSIL
FOR S9A-07/13/72-20:57:20 (0,)

   FUNCTION PF          ENTRY POINT 000155

   STORAGE USED: CODE(1) 000162; DATA(0) 000072; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   ALOG
    0004   SQRT
    0005   NWDU$
    0006   NIO2$
    0007   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000030 1F       0000 R 000022 A       0000 R 000001 A1      0000 R 000002 A2      0000 R 000003 A3
    0000 R 000004 A4       0000 R 000005 A5      0000 R 000023 B       0000 R 000006 B1      0000 R 000007 B2
    0000 R 000010 B3       0000 R 000011 B4      0000 R 000012 B5      0000 R 000024 C       0000 R 000013 C1
    0000 R 000014 C2       0000 R 000017 DT      0000   000061 INJP$   0000 R 000027 P       0000 R 000000 PF
    0000 R 000025 RHO1     0000 R 000020 THETA   0000 R 000021 THETA1  0000 R 000015 TO      0000 R 000016 T01
    0000 R 000026 Z


 00101          FUNCTION PF(RHO,T)
 00101     C
 00101     C       THIS FUNCTION SUBPROGRAM COMPUTES :
 00101     C       PRESSURE AS A FUNCTION OF DENSITY (SLUG/CU.FT) AND TEMPERATURE
 00101     C            (R) OF DOW CORNING 200 SILICON OIL (1 CS)
 00101     C                                    UNITS LBF/SQ.FT
 00101     C            TEMPERATURE .GE. 359.67 AND .LE. 859.67
 00101     C            TEMP. GE. 360.67 AND LE. 860.67
 00103          DATA A1,A2,A3,A4,A5 /12.35,2.98333,1.1,-0.48333,0.1/,B1,B2,B3,B4,
 00103         1B5 /-1.5,-0.01333,-1.18,0.57333,-0.1/,C1,C2 /0.7767,-0.0288/,
 00103         2TO,T01,DT /559.67,609.67,50.0/
 00123          THETA  = (T-TO)/DT
 00124          THETA1 = (T-T01)/DT
 00125          A  = ((((A5*THETA+A4)*THETA+A3)*THETA+A2)*THETA+A1)
 00126          B  = ((((B5*THETA+B4)*THETA+B3)*THETA+B2)*THETA+B1)
 00127          C  = C1+C2*THETA1
 00130          RHO1 = RHO*32.174/62.42
 00131          Z  = A*A+2.0*B*ALOG(RHO1/C)*1000.0
 00132          P  = (-A+SQRT(Z))*1000.0/B
 00133          PF = (P+14.696)*144.0
 00134          IF (T.LT.360.67.OR.T.GT.860.67.OR.PF.GT.146116.224.OR.PF.GT.110116
 00134         1.224.AND.T.LT.460.67) WRITE(6,1) T,PF
 00141        1 FORMAT (1H0,43HPRESSURE OF SILICON OIL, OUT OF RANGE, T = ,F10.5,
 00141         16H, P = ,F15.5,/)
 00142          RETURN
 00143          END
```

```
END OF COMPILATION:         NO  DIAGNOSTICS.

@HDG,P  ******  POLY  ******
```

```
@FOR,S ME*NASA5.POLY,ME*NASA5.POLY
FOR S9A-07/13/72-20:57:23 (0,)

   FUNCTION POLY        ENTRY POINT 000036

   STORAGE USED: CODE(1) 000044; DATA(0) 000015; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000012 107G      0000   000003 INJP$     0000 I 000002 K        0000 I 000001 L        0000 R 000000 POLY


00101      1*           FUNCTION POLY(N,A,X)
00101      2*     C
00101      3*     C   THIS SUBROUTINE EVALUATES POLYNOMIAL
00101      4*     C     POLY = A(1)+A(2)*X+A(3)*X**2+.....+A(N)*X**(N-1)
00101      5*     C
00103      6*           DIMENSION A(N)
00104      7*           POLY = 0.
00105      8*           L = N
00106      9*           DO 1 K=1,N
00111     10*           POLY = POLY*X+A(L)
00112     11*         1 L = L-1
00114     12*           RETURN
00115     13*           END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  @INCID  ******
```

```
QFOR,S ME*NASA5.QINCID,ME*NASA5.QINCID
FOR S9A-07/13/72-20:57:27 (0,)

   SUBROUTINE QINCID    ENTRY POINT 001001

   STORAGE USED: CODE(1) 001027; DATA(0) 000665; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003   QIN    001610
    0004   TC     000042

   EXTERNAL REFERENCES (BLOCK, NAME)

    0005   YINT
    0006   SHADE
    0007   DEFINT
    0010   NRBU$
    0011   NIO2$
    0012   NBSP$
    0013   NIO1$
    0014   NREW$
    0015   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000036 10L      0001   000036 123G     0001   000064 142G     0001   000124 160G     0001   000132 165G
    0001   000151 173G     0001   000057 20L      0001   000166 203G     0001   000073 22L      0001   000273 225G
    0001   000337 240G     0001   000354 247G     0001   000404 263G     0001   000230 30L      0001   000547 301G
    0001   000255 32L      0001   000730 324G     0001   000741 330G     0001   000313 36L      0001   000325 38L
    0001   000507 58L      0001   000633 70L      0001   000643 80L      0004   000003 ABEMF    0000 R 000000 ANG
    0007 R 000000 DEFINT   0000 I 000605 I        0004 I 000001 ICASE    0000 I 000603 IFILE    0000   000633 INJP$
    0000 I 000604 IP       0004 I 000000 ITAPE    0000 I 000617 J        0000 I 000610 K        0000 I 000614 KO
    0000 I 000615 K1       0000 I 000612 M1       0000 I 000613 M2       0000 I 000611 NP       0000 I 000606 NS
    0003 I 001605 NSRD     0003 I 001604 NTM      0000 I 000607 N1       0000 R 000616 PANG     0004   000004 PHIN
    0000 R 000343 QA       0000 R 000077 QALB     0003 R 000454 QIFN     0003 R 001274 QITB     0000 R 000463 QP
    0000 R 000151 QPLN     0000 R 000223 QS       0003 R 000144 QSFN     0003 R 000764 QSTB     0000 R 000025 QSUN
    0003   001606 QTO      0003 R 000000 TM       0004 R 000002 TO       0003   001607 TX       0005 R 000000 YINT


 00101           SUBROUTINE QINCID(MSTOTR,PHN)
 00101     C
 00101     C  THIS SUBROUTINE PROVIDES :
 00101     C    1- DATA TRANSFER FROM THE SRI INCIDENT RADIATION COMPUTER PROGRAM
 00101     C    2- AVERAGING OF RADIANT FLUX OVER CIRCUMFERENCE OF TUBE CROSS-
 00101     C    SECTION
 00101     C
 00103           PARAMETER NTP = 10
 00104           PARAMETER MAXSID = 20
 00105           PARAMETER MAXSD1 = MAXSID+1
 00106           COMMON /QIN/ TM(100),QSFN(100,2),QIFN(100,2),QSTB(100,2),
```

```
00106            1  QITB(100,2),NTM,NSRD,QTO,TX
00107               COMMON /TC/ ITAPE,ICASE,TO,ABEMF,PHIN(NTP,3)
00110               DIMENSION ANG(MAXSD1),QSUN(MAXSD1,2),QALB(MAXSD1,2),
00110            1  QPLN(MAXSD1,2),QS(4,MAXSID),QA(4,MAXSID),QP(4,MAXSID)
00111               IFILE = ITAPE
00112               IF (ITAPE.LE.0) IFILE = NSRD+2
00114               IP = 1
00115               IF (ABS(PHN).GT.0.0) IP = 2
00117               IF (ICASE.LE.1) GO TO 20
00121               TM(I) = -(10.0**30)
00122               DO 16 I = 2,ICASE
00125      10       TM(2) = TM(1)
00126               READ (IFILE) NS,TM(1)
00132               IF (TM(1).GT.TM(2)) GO TO 10
00134      16       CONTINUE
00136               BACKSPACE IFILE
00137      20       IF (MSTOTR.EQ.2) GO TO 30
00141               DO 21 I = 1,2
00144      21       READ (IFILE)
00147               N1 = 2
00150      22       READ (IFILE) NS,TM(1)
00154               N1 = N1+1
00155               IF (TM(1).LT.TO.AND.N1.LT.NTM-1) GO TO 22
00157               DO 24 I = 1,3
00162      24       BACKSPACE IFILE
00164               DO 26 I = 1,4
00167      26       READ (IFILE) NS,TM(I),(QS(I,K),QA(I,K),QP(I,K),K=1,NS)
00202               DO 28 K = 1,NS
00205               QSUN(K,1) = YINT(TM,QS(1,K),4,4,TO)
00206               QALB(K,1) = YINT(TM,QA(1,K),4,4,TO)
00207      28       QPLN(K,1) = YINT(TM,QP(1,K),4,4,TO)
00211               TM(1) = 0.0
00212               NTM = 1
00213      30       IF (ICASE.GT.1.OR.MSTOTR.EQ.1) GO TO 32
00215               READ (IFILE) NS
00220               BACKSPACE IFILE
00221      32       NP = NS/2
00222               M1 = (NP-1)/2
00223               M2 = NP/2
00224               DO 34 I = 0,NS
00227      34       ANG(I+1) = FLOAT(I*360+180)/NS
00231               IF (IP.EQ.1) GO TO 38
00233               KO = 0
00234      36       KO = KO+1
00235               IF (ANG(KO)+ANG(1).LE.PHN) GO TO 36
00237      38       DO 90 I = 1,NTM
00242               IF (MSTOTR.EQ.2) READ (IFILE) NS,TM(I),(QSUN(K,1),QALB(K,1),
00242            1  QPLN(K,1),K=1,NS)
00255               IF (IP.EQ.1) GO TO 58
00257               QSUN(NS+1,1) = QSUN(1,1)
00260               QALB(NS+1,1) = QALB(1,1)
00261               QPLN(NS+1,1) = QPLN(1,1)
00262               DO 54 K = 1,NS
00265               K1 = MIN(MAX(MOD(K+KO-2,NS),1),NS-2)
00266               PANG = ANG(K)+PHN
00267               IF (PANG.GE.ANG(NS+1)) PANG = PANG-360.0
00271               QSUN(K,2) = YINT(ANG(K1),QSUN(K1,1),4,4,PANG)
```

```
00272                 QALB(K,2) = YINT(ANG(K1),QALB(K1,1),4,4,PANG)
00273     54          QPLN(K,2) = YINT(ANG(K1),QPLN(K1,1),4,4,PANG)
00275     58          CALL SHADE(QSUN(1,IP),NS)
00276                 CALL SHADE(QALB(1,IP),NS)
00277                 CALL SHADE(QPLN(1,IP),NS)
00300                 DO 90 J = 1,NSRD
00303                 N1 = NP*(J-1)+1
00304                 IF (M1.EQ.M2) GO TO 70
00306                 QSFN(I,J) = YINT(ANG(M1),QSUN(N1+M1-1,IP),4,4,90.0)
00307                 QIFN(I,J) = YINT(ANG(M1),QALB(N1+M1-1,IP),4,4,90.0)+
00307          1      YINT(ANG(M1),QPLN(N1+M1-1,IP),4,4,90.0)
00310                 GO TO 80
00311     70          QSFN(I,J) = QSUN(N1+M1,IP)
00312                 QIFN(I,J) = QALB(N1+M1,IP)+QPLN(N1+M1,IP)
00313     80          QSTB(I,J) = DEFINT(QSUN(N1,IP),0.5,NP)
00314     90          QITB(I,J) = DEFINT(QALB(N1,IP),0.5,NP)+
00314          1      DEFINT(QPLN(N1,IP),0.5,NP)
00317                 REWIND IFILE
00320                 IF (MSTOTR.EQ.2) RETURN
00322                 NTM = 4
00323                 DO 100 I = 2,4
00326                 TM(I) = 20*(I-1)
00327                 DO 100 J = 1,NSRD
00332                 QSFN(I,J) = QSFN(1,J)
00333                 QIFN(I,J) = QIFN(1,J)
00334                 QSTB(I,J) = QSTB(1,J)
00335     100         QITB(I,J) = QITB(1,J)
00340                 RETURN
00341                 END

     END OF COMPILATION:        NO  DIAGNOSTICS.


QHDG,P  ******  QRAD  ******
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```
QFOR,S ME*NASA5.QRAD,ME*NASA5.QRAD
FOR S9A-07/13/72-20:57:31 (0,)

   SUBROUTINE QRAD       ENTRY POINT 000772

   STORAGE USED: CODE(1) 001013; DATA(0) 001077; BLANK COMMON(2) 001115

    COMMON BLOCKS:

    0003    QRD     003721
    0004    QIN     001610
    0005    ABSRST  000601
    0006    SSF     000010
    0007    AVGABS  000251

   EXTERNAL REFERENCES (BLOCK, NAME)

    0010    INTERP
    0011    YINT
    0012    EMIT
    0013    AVGEMT
    0014    ABSORB
    0015    TRMATX
    0016    MTXINV
    0017    EXITAV
    0020    DEFNT
    0021    NERR2$
    0022    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000245 100L      0001     000010 122G      0001     000012 126G      0001     000046 135G      0001     000055 142G
    0001     000073 147G      0001     000123 156G      0001     000112 2L        0001     000304 206G      0001     000306 211G
    0001     000346 225G      0001     000362 235G      0001     000366 241G      0001     000422 252G      0001     000434 256G
    0001     000443 261G      0001     000524 273G      0001     000536 277G      0001     000632 313G      0001     000633 316G
    0001     000645 324G      0001     000702 337G      0001     000733 346G      0001     000735 352G      0001     000332 500L
    0001     000344 550L      0001     000360 600L      0001     000407 700L      0001     000641 810L      0001     000673 820L
    0001     000717 910L      0006     000002 ALPFN     0005     000000 ALPHFN    0005     000226 ALPHMP    0002     000562 AUX2
    0000 R   000163 AX1       0000 R   000327 AX2       0000 R   000473 AX3       0000 R   000637 AX4       0002     000752 COB
    0002     001107 COH       0002     000574 CONFN     0002     000740 CONMP     0002     001070 CPO       0003 R   003465 CSF
    0020 R   000000 DEFNT     0002     001072 DELTA     0002     000764 DOB       0002     001110 DXI       0002     001053 DXIMP
    0002     001052 DXITB     0003 R   003464 DXX2      0003     003472 DXX21     0002     001051 DZ        0003     003463 DZMFN
    0003 R   003410 EBFN      0003 R   003441 EBMP      0012 R   000000 EMIT      0005     000461 EMITFN    0005     000512 EMITMP
    0003 R   003467 EXTIFN    0003 R   003471 EXTIMP    0003 R   003466 EXTSFN    0003 R   003470 EXTSMP    0005 R   000517 EXTVCT
    0002     001103 FENTH     0002     001045 FFO       0002     001101 FLUX      0002     001041 FMACH     0002     001040 FNU
    0002     001046 FOF       0002     000012 FP        0002     001042 FPR       0002     001037 FR        0002     001050 FRAD
    0002     001111 FRD       0002     001036 FRE       0002     001104 FREJ      0002     001043 FRL       0002     001044 FRM
    0002     000036 FT        0002     000024 FW        0002     001113 FXHW      0002     001112 FXOH      0002     001047 FZ
    0002     001105 HFN       0000 I   001006 I         0002     001003 IFLOW     0000 I   001007 III       0000 I   001024 IJK
    0000 I   001022 IL        0000     001046 INJP$     0000 I   001005 J         0000 I   001023 JL        0000 I   001016 K
    0000 I   001025 KJL       0000 I   001021 KL        0000 I   001017 L         0002     001024 LC        0003 I   003461 LCT
    0002     001032 LIM       0002     001031 LIMWRT    0002     001011 LL1       0002     001012 LL2       0002     001013 LL3
    0002     001014 LL4       0002     001015 LL5       0002     001016 LL6       0002     001017 LL7       0002     001006 LMP
```

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 0002     001004 LT       0002     001005 LTB      0002     001007 LTBMZ    0002     001010 LTB2MZ   0003 I 003462 LTT
 0003 I 003460 MCVRD    0002     001030 MM1      0002     001033 MOD      0002     001025 MSTOTR   0002 I 000777 MZ
 0002     001034 NCCZ     0002     001035 NCONV    0002     001002 NCTL     0002     001026 NCTM     0002     001023 NEQUS
 0002     001027 NM1      0002 I 001001 NRMP     0002     001020 NRMP1    0002     001022 NRMP2    0002     001000 NRTB
 0002     001021 NRTB1    0004 I 001605 NSRD     0004 I 001604 NTM      0002 I 000776 NX       0002     001063 PHIF
 0002     001062 PHIM     0002     001071 PI       0002     001065 PO       0000 R 000017 QFN      0004 R 000454 QIFN
 0004 R 001274 QITB     0000 R 000012 QMP      0002     001102 QREF     0002 R 000360 QRFN     0002 R 000524 QRMP
 0004 R 000144 QSFN     0004 R 000764 QSTB     0004 R 001606 QTO      0002     001074 RDTWRT   0002     001114 RHOFN
 0002     001067 RHOO     0002     001073 RLIMIT   0002     001100 RTEND    0006     000003 R1       0006     000000 R2
 0003 R 003473 SS       0003 R 003670 SSTT     0006     000001 T        0000 R 001004 TALB     0002 R 000132 TEMP
 0007 R 000100 TFIN     0002     001077 TI       0002     001076 TINTL    0004 R 000000 TM       0002 R 000276 TMP
 0000 R 000000 TMPP     0007 R 000244 TPR      0002     001075 TREF     0003 R 000000 TRMTX    0000 R 001003 TSOL
 0002     000050 TW       0004 R 001607 TX       0002 R 001064 TO       0006     000006 WWA      0006     000007 WWB
 0002     001066 WO       0000 R 001012 XCFN     0000 R 001013 XCMP     0002 R 000536 XIFN     0002     000005 XIMP
 0002     000000 XITB     0002     001106 XL       0002     001054 XRE      0006     000005 XSMP     0006 R 000004 XSPM
 0000 R 001014 XXCFN    0000 R 001015 XXCMP    0007 R 000062 XXFN     0007     000000 XXMP     0007     000071 XXXFN
 0007     000031 XXXMP    0002     001057 XX10     0002     001060 XX11     0002     001061 XX12     0003 R 003446 XX2
 0002     001055 XX3      0002     001056 XX4      0011 R 000000 YINT     0000 R 001020 Z        0002 R 000550 ZETA
 0000 R 001010 ZFN      0000 R 001011 ZMP      0003 R 003453 ZZ2
```

```
00101            SUBROUTINE QRAD
00101      C
00101      C   THIS SUBROUTINE COMPUTES :
00101      C     1- INVERSION OF TRANSFER MATRIX
00101      C     2- SOLUTION OF RADIOSITY EQUATION
00101      C     3- GRID MAPPING
00101      C
00101      C
00101      C     NET RADIANT HEAT LOSS, AVERAGED OVER REPRESENTATIVE AREA ELEMENT
00101      C        (OVER BOTH SIDES OF THE FIN, BOTH HALVES OF THE TUBE)
00101      C
00103            COMMON XITB(5),XIMP(5),FP(10),FW(10),FT(10),TW(10,5),TEMP(10,10),
00103           1       TMP(10,5),QRFN(10,10),QRMP(10),XIFN(10),ZETA(10),AUX2(10),
00103           2       CONFN(10,10),CONMP(10),COB(10),DOB(10)
00104            COMMON NX,MZ,NRTB,NRMP,NCTL,IFLOW,LT,LTB,LMP,LTBMZ,LTB2MZ,LL1,
00104           1      LL2,LL3,LL4,LL5,LL6,LL7,NRMP1,NRTB1,NRMP2,NEQUS,LC,MSTOTR,
00104           2      NCTM,NM1,MM1,LIMWRT,LIM,MOD,NCCZ,NCONV
00105            COMMON FRE,FR,FNU,FMACH,FPR,FRL,FRM,FFO,FOF,FZ,FRAD,DZ,DXITB,DXIMP
00105           1       ,XRE,XX3,XX4,XX10,XX11,XX12,PHIM,PHIF,TO,PO,WO,RHOO,CPO,PI
00105           2       ,DELTA,RLIMIT,RDTWRT,TREF,TINTL,TI,RTEND,FLUX,QREF,FENTH,
00105           3       FREJ,HFN,XL,COH,DXI,FRD,FXOH,FXHW,RHOFN
00106            COMMON /QRD/ TRMTX(30,60),EBFN(5,5),EBMP(5),XX2(5),ZZ2(5),
00106           1            MCVRD,LCT,LTT,DZMFN,
00106           2            DXX2,CSF,EXTSFN,EXTIFN,EXTSMP,EXTIMP,DXX21,SS(5,5,5)
00106           3            ,SSTT(5,5)
00107            COMMON /QIN/TM(100), QSFN(100,2), QIFN(100,2), QSTB(100,2),
00107           1           QITB(100,2), NTM, NSRD, QTO, TX
00110            COMMON /ABSRST/ALPHFN(5,5,6),ALPHMP(5,31),EMITFN(5,5),EMITMP(5),
00110           1              EXTVCT(50)
00111            COMMON /SSF/R2, T, ALPFN,R1,XSPM,XSMP,WWA,WWB
00112            COMMON/AVGABS/XXMP(5,5),XXXMP(5,5),XXFN(7),XXXFN(7),
00112           1             TFIN(10,10),TPR(5)
00113            DIMENSION TMPP(10),QMP(5),QFN(10,10),
00113           1         AX1(100),AX2(100),AX3(100),AX4(100)
```

```
00114        DATA TSOL,TALB/10400.0,480.0/
00114   C
00117        IF(LTT.GT.1) GO TO 910
00121        DO 1  J = 1,5
00124        QMP(J)  = 0.0
00125        DO 1  I = 1,5
00130      1 QFN(J,I)= 0.0
00130   C
00133        CALL INTERP(NX,MZ,XIFN,ZETA,TEMP,5,5,XX2,ZZ2,TFIN)
00133   C
00134        DO 5    J = 1,MZ
00137      5 TMPP(J)    = TMP(J,NRMP)
00141        DO 10   J = 1,5
00144        TPR(J)     = YINT(ZETA,TMPP,MZ,3,ZZ2(J))
00145        EBMP(J)    = TPR (J)**4
00146        DO 10   I = 1,5
00151     10 EBFN(J,I) = TFIN(J,I)**4
00151   C
00154        III      = 1
00155      2 DO 3 J = 1,NTM
00160        AX1(J)= QIFN(J,III)
00161        AX2(J)= QSFN(J,III)
00162        AX3(J)= QITB(J,III)
00163      3 AX4(J)= QSTB(J,III)
00165        EXTIFN = YINT(TM,AX1,NTM,3,TX)/QTO
00166        EXTSFN = YINT(TM,AX2,NTM,3,TX)/QTO
00167        EXTIMP = YINT(TM,AX3,NTM,3,TX)/QTO
00170        EXTSMP = YINT(TM,AX4,NTM,3,TX)/QTO
00171        ZFN      = EXTSFN+EXTIFN
00172        ZMP      = EXTSMP+EXTIMP
00173        XCFN     = (EXTSFN*EMIT(TSOL)+EXTIFN*EMIT(TALB))/ZFN
00174        XCMP     = (EXTSMP*EMIT(TSOL)+EXTIMP*EMIT(TALB))/ZMP
00174   C
00175        GO TO (100,500),LCT
00175   C
00176    100 CALL AVGEMT(TO)
00177        XXCFN    = (EXTSFN*XXFN(7)+EXTIFN*XXFN(6))/ZFN
00200        XXCMP    = (EXTSMP*XXFN(7)+EXTIMP*XXFN(6))/ZMP
00201        CALL ABSORB(TO,XCFN,XCMP,XXCFN,XXCMP)
00202        CALL TRMATX
00203        IF (LTT.NE.0) GO TO 500
00205        DO 115    I = 1,30
00210        DO 110    J = 31,60
00213    110 TRMTX(I,J) = 0.0
00215        K          = I+30
00216    115 TRMTX(I,K) = 1.0
00220        CALL MTXINV(30,60)
00221        LCT          = 2
00221   C
00222    500 CALL EXITAV
00223        GO TO (550,600),LCT
00223   C
00224    550 DO 555     I = 1,30
00227    555 TRMTX(I,31) = EXTVCT(I)
00231        CALL MTXINV (30,31)
00232        L            = 31
00233        GO TO 700
```

```
00233      C
00234        600 DO 610   I = 1,30
00237            Z          = 0.0
00240            DO 605   J = 1,30
00243            K          = J+30
00244        605 Z          = Z+TRMTX(I,K)*EXTVCT(J)
00246        610 TRMTX(I,1) = Z
00250            L          = 1
00250      C
00250      C
00251        700 DO 730  J=1,5
00254            KL        = J+25
00255            DO 720 IL=1,5
00260            DO 715 JL=1,5
00263            K         = (IL-1)*5+JL
00264        715 AX1(JL) = CSF*SS(IL,JL,J)*TRMTX(K,L)
00266            AX3(IL) = SSTT(J,IL)*TRMTX(IL+25,L)
00267        720 AX2(IL) = DEFNT(AX1,0.25,5)
00271            QMP(J)    = -(ZMP+DEFNT(AX2,DXX2,5)+AX2(1)*DXX2/2.0+DEFNT(AX3,
00271          1            0.25,5)-TRMTX(KL,L))/2.0+QMP(J)
00272            DO 730  I=1,5
00275            IJK       = (I-1)*5+J
00276            DO 725 JL=1,5
00301            KJL       = 25+JL
00302        725 AX1(JL) = SS(I,J,JL)*TRMTX(KJL,L)
00304        730 QFN(J,I) = -(ZFN+DEFNT(AX1,0.25,5)-TRMTX(IJK,L))+QFN(J,I)
00304      C
00304      C
00307            CALL INTERP(5,5,XX2,ZZ2,QFN,NX,MZ,XIFN,ZETA,QRFN)
00310            IF(MCVRD.LE.0) GO TO 810
00310      C
00312            DO 800  I = 1,MCVRD
00315            DO 800  J = 1,MZ
00320        800 QRFN(J,I) = 0.0
00320      C
00323        810 DO 815  J = 1,MZ
00326        815 QRMP(J)    = YINT(ZZ2,QMP,5,3,ZETA(J))
00330            IF (III.EQ.2) GO TO 820
00332            IF (NSRD.EQ.1) GO TO 820
00334            III          = 2
00335            GO TO 2
00335      C
00336        820 DO 825 J   = 1,MZ
00341            K            = MCVRD+1
00342        825 QRFN(J,K) = QRFN(J,K)*XSPM
00344            RETURN
00345        910 DO 915 J=1,MZ
00350            QRMP(J)    = 0.0
00351            DO 915 I=1,NX
00354        915 QRFN(J,I) = 0.0
00357            RETURN
00360            END
```

END OF COMPILATION: NO DIAGNOSTICS.

QHDG,P ****** REFP ******

```
@FOR,S ME*NASA5.REFP,ME*NASA5.REFP
FOR S9A-07/13/72-20:57:38 (0,)

   SUBROUTINE REFP       ENTRY POINT 000316

   STORAGE USED: CODE(1) 000367; DATA(0) 000163; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   CPAIR
    0004   POLY
    0005   NEXP6$
    0006   EXP
    0007   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000076 2L       0001   000214 20L      0001   000065 223G     0001   000154 3L       0001   000172 4L
    0000 R 000066 A0       0000 R 000067 A1       0000 R 000100 A10      0000 R 000101 A11      0000 R 000070 A2
    0000 R 000071 A3       0000 R 000072 A4       0000 R 000073 A5       0000 R 000074 A6       0000 R 000075 A7
    0000 R 000076 A8       0000 R 000077 A9       0000 R 000064 CF1      0000 R 000065 CF2      0003 R 000000 CPAIR
    0000 R 000056 CP1      0000 R 000057 CP2      0000 R 000060 CP3      0000 R 000061 CP4      0000 R 000110 DH
    0000 R 000063 DT       0000 R 000104 ELEVM    0000 R 000106 GEOH     0000 R 000105 GEOHM    0000 R 000007 GH
    0000 R 000031 GT       0000 R 000052 G0       0000 R 000000 H        0000 I 000107 I        0000   000144 INJP$
    0000 I 000111 J        0000 R 000102 MWT      0000 R 000041 P        0000 R 000113 PATM     0004 R 000000 POLY
    0000 R 000116 PSL      0000 R 000115 PZ       0000 R 000054 RU       0000 R 000055 RU1      0000 R 000020 T
    0000 R 000112 TMB      0000 R 000103 TMK      0000 R 000062 T0       0000 R 000053 WM0      0000 R 000114 Z


00101           SUBROUTINE REFP (ELEV,REFTP,REFPR,REFVIS,REFRHO,REFK,REFCP,
00101          1              REFGAM)
00101     C
00101     C   THIS SUBROUTINE COMPUTES :
00101     C       PROPERTIES OF ATMOSPHERIC AIR EVALUATED AT THE HIGH SPEED
00101     C       REFERENCE TEMPERATURE
00101     C                                    ELEVATION IN FEET
00101     C                                    REFERENCE TEMP. IN DEGREES R.
00101     C                                    PRANDTL NUMBER DIMENSIONLESS
00101     C                                    DYN. VISCOSITY IN LBM/ FT.SEC.
00101     C                                    DENSITY IN LBM/CUBIC FOOT
00101     C                                    THERMAL COND.IN BTU/SEC FT DEG R
00101     C                                    SPECIFIC HEAT IN BTU/LBM DEG R
00101     C
00103           DIMENSION H(7),GH(9),T(9),GT(8),P(9)
00104           DATA H(1),H(2),H(3),H(4),H(5),H(6),H(7) /0.0,1.0,-1.5731262E-07,2.
00104          14656553E-14,-3.8667054E-21,6.0621354E-28,-9.5013649E-35/,GH(1),GH(
00104          22),GH(3),GH(4),GH(5),GH(6),GH(7),GH(8),GH(9) /0.0,11.0,20.0,32.0,4
00104          37.0,52.0,61.0,79.0,90.0/,T(1),T(2),T(3),T(4),T(5),T(6),T(7),T(8),T
00104          4(9) /288.15,216.65,216.65,228.65,270.65,270.65,252.65,180.65,180.6
00104          55/,GT(1),GT(2),GT(3),GT(4),GT(5),GT(6),GT(7),GT(8) /-6.5,0.0,1.0,2
00104          6.8,0.0,-2.0,-4.0,0.0/,P(1),P(2),P(3),P(4),P(5),P(6),P(7),P(8),P(9)
```

```
00104          7 /2116.22,472.681,114.345,18.1298,2.31631,1.23225,0.380323,0.02167
00104          82,0.0027138/,G0,WM0,RU,RU1 /9.80665,28.9644,8314.32,1545.31/,CP1,C
00104          9P2,CP3,CP4 /0.239573,-0.000127,0.000051,0.000014/,T0,DT /270.0,90.
00104          10/,CF1,CF2 /1000.0,0.671969/
00173           DATA  A0,A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,A11/
00173          1       0.10E+01,  0.3533367370E-01,  -0.7474788290E-03,
00173          2       0.2121572232E-03,  -0.1325255219E-04,  0.5344159692E-06,
00173          3       -0.1322745646E-07,  0.1965359762E-09,  -0.1723714966E-11,
00173          4       0.8707590786E-14,  -0.2341816445E-16,  0.2597772972E-19/,
00210           REAL MWT
00211           TMK    =  REFTP/1.8
00212           REFVIS =  ((1.458E-06*TMK**1.5)/(TMK+110.4))*CF2
00213           REFK   = ((6.325E-07*TMK**1.5)/(TMK+245.4*10.0**(-12.0/TMK)))*CF2
00214           REFCP   =  CPAIR(REFTP)
00215           IF (ELEV .GT. 301000.)  GO TO 20
00217           ELEVM  = ELEV*0.3048
00220           GEOHM  = POLY(7,H,ELEVM)
00221           GEOH   = GEOHM/0.3048
00222           DO 1  I=1,9
00225           DH     = GH(I)-GEOHM/CF1
00226           IF (DH.GT.0.0) GO TO 2
00230         1 CONTINUE
00232         2 J      = I-1
00233           DH     = GH(J)-GEOHM/CF1
00234           TMB    =  T(J)-GT(J)*DH
00235           IF (J.EQ.2.OR.J.EQ.5.OR.J.EQ.8) GO TO 3
00237           PATM   = P(J)*(T(J)/TMB)**(G0*WM0*CF1/(RU*GT(J)))
00240           GO TO 4
00241         3 PATM   = P(J)*EXP(G0*WM0*DH*CF1/(RU*T(J)))
00242         4 REFRHO = WM0*PATM/(RU1*REFTP)
00243           REFPR  =  REFVIS*REFCP/REFK
00244           REFGAM  =  REFCP/(REFCP-0.0686)
00245           RETURN
00246        20 Z      =  ELEV/(3280.8399)
00247           MWT    =  28.9644-0.0309491*(Z-90.0)
00250           PZ     =  1.0/((A0+Z*(A1+Z*(A2+Z*(A3+Z*(A4+Z*(A5+Z*(A6+Z*(A7+Z
00250          1          *(A8+Z*(A9+Z*(A10+Z*A11))))))))))))**4)
00251           PSL    =  2116.22657
00252           PATM   =  PSL*PZ
00253           REFRHO =  PATM*MWT/(1545.31*REFTP)
00254           REFPR  =  REFVIS*REFCP/REFK
00255           REFGAM  =  REFCP/(REFCP-(1.98585/MWT))
00256           RETURN
00257           END

        END OF COMPILATION:        NO  DIAGNOSTICS.


QHDG.P  ******  RHOF/CFFC43  ******
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```
****** RHOF/CFFC43 ******                                                      DATE 071372        PAGE     1

@FOR,S ME*NASA5.RHOF/CFFC43,ME*NASA5.RHOF/CFFC43
FOR S9A-07/13/72-20:57:42 (0,)

   FUNCTION RHOF         ENTRY POINT 000014

   STORAGE USED: CODE(1) 000016; DATA(0) 000011; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000004 INJP$     0000 R 000000 RHOF      0000 R 000001 X1       0000 R 000002 X2


 00101      1*          FUNCTION RHOF(P,T)
 00101      2*     C
 00101      3*     C       THIS FUNCTION SUBPROGRAM COMPUTES :
 00101      4*     C       DENSITY AS A FUNCTION OF PRESSURE (LBF/SQ.FT) AND
 00101      5*     C           TEMPERATURE (R) OF FC-43
 00101      6*     C                                       UNITS SLUG/QU.FT
 00101      7*     C
 00103      8*          DATA X1,X2 /157.0883,-0.076167/
 00106      9*          RHOF = (X1+X2*T)/32.174
 00107     10*          RETURN
 00110     11*          END
      END OF COMPILATION:        NO  DIAGNOSTICS.


 @HDG,P  ******  RHOF/CFFC75  ******
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****** RHOF/CFFC75 ******                                                          DATE 071372      PAGE    1

@FOR,S ME*NASA5.RHOF/CFFC75,ME*NASA5.RHOF/CFFC75
FOR S9A-07/13/72-20:57:44 (0,)

  FUNCTION RHOF        ENTRY POINT 000014

  STORAGE USED: CODE(1) 000016; DATA(0) 000011; BLANK COMMON(2) 000000

  EXTERNAL REFERENCES (BLOCK, NAME)

   0003   NERR3$

  STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

   0000   000004 INJP$     0000 R 000000 RHOF      0000 R 000001 X1       0000 R 000002 X2


00101      1*           FUNCTION RHOF(P,T)
00101      2*     C
00101      3*     C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*     C        DENSITY AS A FUNCTION OF PRESSURE (LBF/SQ.FT) AND
00101      5*     C             TEMPERATURE (R) OF FC-75
00101      6*     C                                         UNITS SLUG/QU.FT
00101      7*     C
00103      8*           DATA X1,X2 /155.522,-0.085/
00106      9*           RHOF = (X1+X2*T)/32.174
00107     10*           RETURN
00110     11*           END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  RHOF/CFHE  ******
```

```
@FOR,S ME*NASA5.RHOF/CFHE,ME*NASA5.RHOF/CFHE
FOR S9A-07/13/72-20:57:47 (0,)

   FUNCTION RHOF        ENTRY POINT 000067

   STORAGE USED: CODE(1) 000077; DATA(0) 000023; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   PF
    0004   CAPPA
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000015 2L       0001     000055 4L       0004 R 000000 CAPPA     0000 R 000005 DIFF      0000 R 000006 DPDRHO
    0000 R 000007 DRHO       0000     000014 INJP$    0000 I 000001 N         0003 R 000000 PF        0000 R 000004 P1
    0000 R 000002 R          0000 R 000000 RHOF       0000 R 000003 RHO1


00101            FUNCTION RHOF(P,T)
00101       C
00101       C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101       C       DENSITY AS A FUNCTION OF PRESSURE (LBF/SQ.FT) AND
00101       C            TEMPERATURE (R) OF HELIUM
00101       C                                    UNITS SLUG/QU.FT
00101       C
00103            N      = 1
00104            R      = 12419.164
00105            RHO1   = P/(R*T)
00106            IF (0.388-RHO1)1,1,2
00111          1 RHO1   = 0.388
00112          2 P1     = PF(RHO1,T)
00113            DIFF   = ABS((P-P1)/P)
00114            IF (DIFF-1.0E-12)4,3,3
00117          3 DPDRHO= 1.0/(RHO1*CAPPA(RHO1,T))
00120            DRHO   = (P-P1)/DPDRHO
00121            RHO1   = RHO1+DRHO
00122            N      = N+1
00123            IF (N-10)2,2,4
00126          4 RHOF   = RHO1
00127            RETURN
00130            END

      END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  RHOF/CFNAK  ******
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```
@FOR,S ME*NASA5.RHOF/CFNAK,ME*NASA5.RHOF/CFNAK
FOR S9A-07/13/72-20:57:49 (0,)

   FUNCTION RHOF        ENTRY POINT 000031

   STORAGE USED: CODE(1) 000040; DATA(0) 000017; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   CAPPA
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0003 R 000000 CAPPA     0000   000011 INJP$     0000 R 000003 P0        0000 R 000006 P1        0000 R 000004 RHO
    0000 R 000000 RHOF      0000 R 000005 TK        0000 R 000001 X1        0000 R 000002 X2


00101      1*             FUNCTION RHOF(P,T)
00101      2*      C
00101      3*      C         THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*      C         DENSITY AS A FUNCTION OF PRESSURE (LBF/SQ.FT) AND
00101      5*      C              TEMPERATURE (R) OF NAK 78.6
00101      6*      C                                         UNITS SLUG/QU.FT
00101      7*      C
00103      8*             DATA X1,X2 /58.773064,-0.008433/,P0 /2116.224/
00107      9*             RHO  = (X1+X2*T)/32.174
00110     10*             TK   = CAPPA(RHO,T)
00111     11*             P1   = P-P0
00112     12*             RHOF = RHO*(1.0+TK*P1)
00113     13*             RETURN
00114     14*             END

      END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  RHOF/CFSIL  ******
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```
@FOR,S ME*NASA5.RHOF/CFSIL,ME*NASA5.RHOF/CFSIL
FOR S9A-07/13/72-20:57:51 (0,)

   FUNCTION RHOF        ENTRY POINT 000122

   STORAGE USED: CODE(1) 000127; DATA(0) 000065; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003    EXP
    0004    NWDU$
    0005    NIO2$
    0006    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000027 1F        0000 R 000022 A          0000 R 000001 A1         0000 R 000002 A2         0000 R 000003 A3
    0000 R 000004 A4        0000 R 000005 A5         0000 R 000023 B          0000 R 000006 B1         0000 R 000007 B2
    0000 R 000010 B3        0000 R 000011 B4         0000 R 000012 B5         0000 R 000024 C          0000 R 000013 C1
    0000 R 000014 C2        0000 R 000017 DT         0000   000054 INJP$      0000 R 000025 P1         0000 R 000026 RHO
    0000 R 000000 RHOF      0000 R 000020 THETA      0000 R 000021 THETA1     0000 R 000015 T0         0000 R 000016 T01


 00101          FUNCTION RHOF(P,T)
 00101      C
 00101      C      THIS FUNCTION SUBPROGRAM COMPUTES :
 00101      C      DENSITY AS A FUNCTION OF PRESSURE (LBF/SQ.FT) AND
 00101      C           TEMPERATURE (R) OF DOW CORNING 200 SILICON OIL (1 CS)
 00101      C                                UNITS SLUG/CU.FT
 00101      C           TEMPERATURE .GE. 359.67 AND .LE. 859.67
 00101      C
 00103          DATA A1,A2,A3,A4,A5 /12.35,2.98333,1.1,-0.48333,0.1/,B1,B2,B3,B4,
 00103         1B5 /-1.5,-0.01333,-1.18,0.57333,-0.1/,C1,C2 /0.7767,-0.0288/,
 00103         2T0,T01,DT /559.67,609.67,50.0/
 00123          THETA  = (T-T0)/DT
 00124          THETA1 = (T-T01)/DT
 00125          A  = ((((A5*THETA+A4)*THETA+A3)*THETA+A2)*THETA+A1)*1.0E-06
 00126          B  = ((((B5*THETA+B4)*THETA+B3)*THETA+B2)*THETA+B1)*1.0E-09
 00127          C  = C1+C2*THETA1
 00130          P1 = P/144.0-14.696
 00131          RHO  = C*EXP(A*P1+0.5*B*P1*P1)
 00132          RHOF = RHO*62.42/32.174
 00133          IF (T.GE.360.67.AND.T.LE.860.67) RETURN
 00135          WRITE (6,1) T
 00140        1 FORMAT (1H0,48HDENSITY OF SILICON OIL, TEMP. OUT OF RANGE, T = ,F8
 00140         1.3,/)
 00141          RETURN
 00142          END

         END OF COMPILATION:        NO  DIAGNOSTICS.
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@FOR,S ME*NASA5.RKS,ME*NASA5.RKS
FOR S9A-07/13/72-20:57:54 (0,)

   SUBROUTINE RKS       ENTRY POINT 000643

   STORAGE USED: CODE(1) 001040; DATA(0) 000064; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003    NERR2$
    0004    NEXP5$
    0005    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000010 10L      0001     000313 110L     0001     000333 120L     0001     000045 126G     0001     000343 130L
    0001     000071 140G     0001     000355 140L     0001     000105 146G     0001     000130 156G     0001     000417 160L
    0001     000150 164G     0001     000177 174G     0001     000500 185L     0001     000510 190L     0001     000013 20L
    0001     000232 205G     0001     000270 217G     0001     000524 220L     0001     000530 230L     0001     000543 240L
    0001     000374 243G     0001     000032 25L      0001     000552 250L     0001     000554 251L     0001     000572 257L
    0001     000604 259L     0001     000623 270L     0001     000456 300L     0001     000615 336G     0001     000054 40L
    0001     000060 45L      0001     000006 5L       0001     000076 50L      0001     000123 70L      0001     000135 80L
    0000 R 000014 AM       0000 R 000007 AMAX     0000 R 000011 C        0000 R 000010 D        0000 R 000001 DDT
    0000 R 000003 DELT     0000 R 000012 E        0000 R 000000 FR10     0000 I 000004 I        0000 I 000005 IFLAG
    0000     000030 INJP$    0000 I 000002 ISYMP    0000 I 000013 J        0000 R 000006 S
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00101              SUBROUTINE RKS(DERIV,CNTRL,Y,DY,A,R,T,DEL,N,IFVD,IBKP,NTRY,       DG000100
00101             1IERR,DELY,PD,SD,YS,YST,DYST,YSIMP)                                DG000200
00103              DIMENSION Y(N),DY(N),A(N),R(N),DELY(N),                          DG000300
00103             1PD(N),SD(N),YS(N),DYST(N),YST(N),YSIMP(N)                        DG000400
00104              EXTERNAL  DERIV, CNTRL                                           DG000500
00104        C     FR10 IS  FIFTH ROOT OF TEN                                       DG000600
00105              FR10=1.5848932                                                   DG000700
00106              IERR=0                                                           DG000800
00106        C
00106        C    THIS SUBROUTINE COMPUTES :
00106        C     RUNGE-KUTTA INTEGRATION (PRIMARY)
00106        C
00106        C       YS  CONTAINS Y VALUES AT LEFT END POINT OF INTEGRATION INTERVAL DG000900
00106        C                                                                      DG001000
00106        C       YSIMP CONTAINS Y FOR SIMPSONS RULE CHECK  CHECK NOT MADE FOR   DG001100
00106        C           FIXED STEP MODE    ISYMP IS CONTROL PARAMETER =1,FIXED,2 VARDG001200
00106        C                                                                      DG001300
00106        C       IF FIXED STEP SIZE GO ONE INTERVAL OF LENGTH DELT AND RETURN TO DG001400
00106        C          CNTRL, IF VAR GO TWO INTERVALS BEFORE RETURN TO CONTRL      DG001500
00106        C                                                                      DG001600
00106        C       IFVD  = 0     VARIABLE INTERVAL                                DG001700
00106        C             = 1     FIXED                                            DG001800
00106        C       IBKP  = 0     CUT INTERVAL ONCE BEFORE REPEAT  (UNDER IFVD=0 ) DG001900
00106        C             = 1     CUT AS REQUIRED                                  DG002000
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00106    C        NTRY  = 1    CONTINUE INTEGRATING                       DG002100
00106    C                2    RETURN FROM RKS                            DG002200
00106    C                3    STEP REPEATED WITH NEW DELT                DG002300
00106    C                4    RESTART                                    DG002400
00106    C        IERR  = 0    NORMAL                                     DG002500
00106    C               -1    DELT=0, RETURN FROM RKS                    DG002600
00106    C                1    A(I)+ R(I)*ABS(Y(I)) = 0. , RETURN FROM RKS DG002700
00107         5  IF(DEL) 20,10,20                                         DG002800
00112        10  IERR=-1                                                  DG002900
00113            GO TO 270                                                DG003000
00114        20  CALL DERIV(Y,DY,T)                                       DG003100
00115            NTRY=1                                                   DG003200
00116            CALL CNTRL(Y,DY,DEL,T,NTRY,IFVD)                         DG003300
00117        25  DDT=DEL                                                  DG003400
00120            IF(IFVD) 40,30,40                                        DG003500
00123        30  ISYMP=2                                                  DG003600
00124            DELT=DEL/2.                                              DG003700
00125            DO 31 I=1,N                                              DG003800
00130        31  SD(I)=0.0                                                DG003900
00132            IFLAG=1                                                  DG004000
00133            S=1.                                                     DG004100
00134            GO TO 45                                                 DG004200
00135        40  ISYMP=1                                                  DG004300
00136            DELT=DEL                                                 DG004400
00137        45  DO 46 I=1,N                                              DG004500
00142            YST(I)=Y(I)                                              DG004600
00143        46  DYST(I)=DY(I)                                            DG004700
00145        50  DO 60 I=1,N                                              DG004800
00150            DELY(I)=DELT*DY(I)                                       DG004900
00151            PD(I)=DELY(I)                                            DG005000
00152        60  CONTINUE                                                 DG005100
00154            GO TO (80,70),ISYMP                                      DG005200
00155        70  DO 71 I=1,N                                              DG005300
00160        71  SD(I)=SD(I)+S*DY(I)                                      DG005400
00162        80  T=T+DELT/2.                                              DG005500
00163            DO 85 I=1,N                                              DG005600
00166            YS(I)=Y(I)                                               DG005700
00167            Y(I)=YS(I)+DELY(I)/2.                                    DG005800
00170        85  CONTINUE                                                 DG005900
00172            CALL DERIV(Y,DY,T)                                       DG006000
00173            DO 90 I=1,N                                              DG006100
00176            DELY(I)=DELT*DY(I)                                       DG006200
00177            PD(I)=PD(I)+2.*DELY(I)                                   DG006300
00200            Y(I)=YS(I)+DELY(I)/2.                                    DG006400
00201        90  CONTINUE                                                 DG006500
00203            CALL DERIV(Y,DY,T)                                       DG006600
00204            DO 95 I=1,N                                              DG006700
00207            DELY(I)=DELT*DY(I)                                       DG006800
00210            PD(I)=PD(I)+2.*DELY(I)                                   DG006900
00211            Y(I)=YS(I)+DELY(I)                                       DG007000
00212        95  CONTINUE                                                 DG007100
00214            T=T+DELT/2.                                              DG007200
00215            CALL DERIV(Y,DY,T)                                       DG007300
00216            DO 100 I=1,N                                             DG007400
00221            DELY(I)=DELT*DY(I)                                       DG007500
00222            PD(I)=PD(I)+DELY(I)                                      DG007600
00223            Y(I)=YS(I)+PD(I)/6.                                      DG007700
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00224        100 CONTINUE                                  DG007800
00226            GO TO (110,120),ISYMP                     DG007900
00227        110 NTRY=1                                    DG008000
00230            CALL DERIV(Y,DY,T)                        DG008100
00231            CALL CNTRL(Y,DY,DEL,T,NTRY,IFVD)          DG008200
00232            GO TO 300                                 DG008300
00233        120 GO TO (130,140),IFLAG                     DG008400
00234        130 S=4.                                      DG008500
00235            IFLAG=2                                   DG008600
00236            CALL DERIV(Y,DY,T)                        DG008700
00237            GO TO 50                                  DG008800
00240        140 CALL DERIV(Y,DY,T)                        DG008900
00241            AMAX =0.0                                 DG009000
00242            DO 180 I=1,N                              DG009100
00245            SD(I)=SD(I)+DY(I)                         DG009200
00246            YSIMP(I)=YST(I)+DELT*SD(I)/3.             DG009300
00247            D   =ABS(Y(I)-YSIMP(I))                   DG009400
00250            C   =A(I)+R(I)*ABS(Y(I))                  DG009500
00251            IF(C   ) 160,150,160                      DG009600
00254        150 IERR=1                                    DG009700
00255            GO TO 270                                 DG009800
00256        160 E   =ABS(D   /C   )                       DG009900
00257            AMAX=AMAX1(AMAX,E)                        DG010000
00260        180 CONTINUE                                  DG010100
00262            IF(AMAX-1.) 215,215,230                   DG010200
00265        215 NTRY= 1                                   DG010300
00266            CALL CNTRL(Y,DY,DEL,T,NTRY,IFVD)          DG010400
00267        300 IF(NTRY-1) 185,185,310                    DG010500
00272        310 IF(NTRY-2) 270,270,330                    DG010600
00275        330 IF(NTRY-3) 340,340,5                      DG010700
00300        340 T=T-DDT                                   DG010800
00301            IF(DEL) 259,10,259                        DG010900
00304        185 GO TO (40,190),ISYMP                      DG011000
00305        190 IF(AMAX-.75) 200,25,220                   DG011100
00310        200 IF(AMAX-.075) 210,25,25                   DG011200
00313        210 DEL=DEL*FR10                              DG011300
00314            GO TO 25                                  DG011400
00315        220 DEL=DEL/FR10                              DG011500
00316            GO TO 25                                  DG011600
00317        230 I =1+ IBKP                                DG011700
00320            GO TO (240,250),I                         DG011800
00321        240 T=T-DEL                                   DG011900
00322            DEL=DEL/FR10                              DG012000
00323            GO TO  259                                DG012100
00324        250 J=1                                       DG012200
00325        251 AM=AMAX/10.**J                            DG012300
00326            IF(1.-AM) 255,257,257                     DG012400
00331        255 J=J+1                                     DG012500
00332            GO TO 251                                 DG012600
00333        257 T=T-DEL                                   DG012700
00334            DEL=DEL/(FR10**J)                         DG012800
00335        259 DO 245 I=1,N                              DG012900
00340            DY(I)=DYST(I)                             DG013000
00341        245 Y(I)=YST(I)                               DG013100
00343            GO TO 25                                  DG013200
00344        270 RETURN                                    DG013300
00345            END                                       DG013400
```

****** RKS ******

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END OF COMPILATION: NO DIAGNOSTICS.

@HDG,P ****** RKSF ******

```
@FOR,S ME*NASA5.RKSF,ME*NASA5.RKSF
FOR S9A-07/13/72-20:57:59 (0,)

   SUBROUTINE RKSF      ENTRY POINT 000643

   STORAGE USED: CODE(1) 001040; DATA(0) 000064; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR2$
    0004   NEXP5$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000010 10L      0001     000313 110L     0001     000333 120L     0001     000045 126G     0001     000343 130L
    0001     000071 140G     0001     000355 140L     0001     000105 146G     0001     000130 156G     0001     000417 160L
    0001     000150 164G     0001     000177 174G     0001     000500 185L     0001     000510 190L     0001     000013 20L
    0001     000232 205G     0001     000270 217G     0001     000524 220L     0001     000530 230L     0001     000543 240L
    0001     000374 243G     0001     000032 25L      0001     000552 250L     0001     000554 251L     0001     000572 257L
    0001     000604 259L     0001     000623 270L     0001     000456 300L     0001     000615 336G     0001     000054 40L
    0001     000060 45L      0001     000006 5L       0001     000076 50L      0001     000123 70L      0001     000135 80L
    0000 R   000014 AM       0000 R   000007 AMAX     0000 R   000011 C        0000 R   000010 D        0000 R   000001 DDT
    0000 R   000003 DELT     0000 R   000012 E        0000 R   000000 FR10     0000 I   000004 I        0000 I   000005 IFLAG
    0000     000030 INJP$    0000 I   000002 ISYMP    0000 I   000013 J        0000 R   000006 S


 00101             SUBROUTINE RKSF(DERIV,CNTRL,Y,DY,A,R,T,DEL,N,IFVD,IBKP,NTRY,     DG000100
 00101            1IERR,DELY,PD,SD,YS,YST,DYST,YSIMP)                              DG000200
 00103             DIMENSION Y(N),DY(N),A(N),R(N),DELY(N),                         DG000300
 00103            1PD(N),SD(N),YS(N),DYST(N),YST(N),YSIMP(N)                       DG000400
 00104             EXTERNAL  DERIV, CNTRL                                          DG000500
 00104        C    FR10 IS  FIFTH ROOT OF TEN                                      DG000600
 00105             FR10=1.5848932                                                  DG000700
 00106             IERR=0                                                          DG000800
 00106        C
 00106        C   THIS SUBROUTINE COMPUTES :
 00106        C    RUNGE-KUTTA INTEGRATION (SECONDARY)
 00106        C       YS  CONTAINS Y VALUES AT LEFT END POINT OF INTEGRATION INTERVAL DG000900
 00106        C                                                                    DG001000
 00106        C       YSIMP CONTAINS Y FOR SIMPSONS RULE CHECK  CHECK NOT MADE FOR   DG001100
 00106        C           FIXED STEP MODE    ISYMP IS CONTROL PARAMETER =1,FIXED,2 VARDG001200
 00106        C                                                                    DG001300
 00106        C       IF FIXED STEP SIZE GO ONE INTERVAL OF LENGTH DELT AND RETURN TO DG001400
 00106        C          CNTRL, IF VAR GO TWO INTERVALS BEFORE RETURN TO CONTRL       DG001500
 00106        C                                                                    DG001600
 00106        C       IFVD  = 0    VARIABLE INTERVAL                                 DG001700
 00106        C             = 1    FIXED                                           DG001800
 00106        C       IBKP  = 0    CUT INTERVAL ONCE BEFORE REPEAT  (UNDER IFVD=0 )  DG001900
 00106        C             = 1    CUT AS REQUIRED                                 DG002000
 00106        C       NTRY  = 1    CONTINUE INTEGRATING                            DG002100
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```
00106    C                 2    RETURN FROM RKS
00106    C                 3    STEP REPEATED WITH NEW DELT
00106    C                 4    RESTART
00106    C       IERR  = 0      NORMAL
00106    C             =-1      DELT=0, RETURN FROM RKS
00106    C                 1    A(I)+ R(I)*ABS(Y(I)) = 0. , RETURN FROM RKS
00107          5  IF(DEL) 20,10,20
00112         10  IERR=-1
00113             GO TO 270
00114         20  CALL DERIV(Y,DY,T)
00115             NTRY=1
00116             CALL CNTRL(Y,DY,DEL,T,NTRY,IFVD)
00117         25  DDT=DEL
00120             IF(IFVD) 40,30,40
00123         30  ISYMP=2
00124             DELT=DEL/2.
00125             DO 31 I=1,N
00130         31  SD(I)=0.0
00132             IFLAG=1
00133             S=1.
00134             GO TO 45
00135         40  ISYMP=1
00136             DELT=DEL
00137         45  DO 46 I=1,N
00142             YST(I)=Y(I)
00143         46  DYST(I)=DY(I)
00145         50  DO 60 I=1,N
00150             DELY(I)=DELT*DY(I)
00151             PD(I)=DELY(I)
00152         60  CONTINUE
00154             GO TO (80,70),ISYMP
00155         70  DO 71 I=1,N
00160         71  SD(I)=SD(I)+S*DY(I)
00162         80  T=T+DELT/2.
00163             DO 85 I=1,N
00166             YS(I)=Y(I)
00167             Y(I)=YS(I)+DELY(I)/2.
00170         85  CONTINUE
00172             CALL DERIV(Y,DY,T)
00173             DO 90 I=1,N
00176             DELY(I)=DELT*DY(I)
00177             PD(I)=PD(I)+2.*DELY(I)
00200             Y(I)=YS(I)+DELY(I)/2.
00201         90  CONTINUE
00203             CALL DERIV(Y,DY,T)
00204             DO 95 I=1,N
00207             DELY(I)=DELT*DY(I)
00210             PD(I)=PD(I)+2.*DELY(I)
00211             Y(I)=YS(I)+DELY(I)
00212         95  CONTINUE
00214             T=T+DELT/2.
00215             CALL DERIV(Y,DY,T)
00216             DO 100 I=1,N
00221             DELY(I)=DELT*DY(I)
00222             PD(I)=PD(I)+DELY(I)
00223             Y(I)=YS(I)+PD(I)/6.
00224        100  CONTINUE
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00226           GO TO (110,120),ISYMP                     DG007900
00227       110 NTRY=1                                    DG008000
00230           CALL DERIV(Y,DY,T)                        DG008100
00231           CALL CNTRL(Y,DY,DEL,T,NTRY,IFVD)          DG008200
00232           GO TO 300                                 DG008300
00233       120 GO TO (130,140),IFLAG                     DG008400
00234       130 S=4.                                      DG008500
00235           IFLAG=2                                   DG008600
00236           CALL DERIV(Y,DY,T)                        DG008700
00237           GO TO 50                                  DG008800
00240       140 CALL DERIV(Y,DY,T)                        DG008900
00241           AMAX =0.0                                 DG009000
00242           DO 180 I=1,N                              DG009100
00245           SD(I)=SD(I)+DY(I)                         DG009200
00246           YSIMP(I)=YST(I)+DELT*SD(I)/3.             DG009300
00247           D    =ABS(Y(I)-YSIMP(I))                  DG009400
00250           C    =A(I)+R(I)*ABS(Y(I))                 DG009500
00251           IF(C    ) 160,150,160                     DG009600
00254       150 IERR=1                                    DG009700
00255           GO TO 270                                 DG009800
00256       160 E    =ABS(D    /C    )                    DG009900
00257           AMAX=AMAX1(AMAX,E)                        DG010000
00260       180 CONTINUE                                  DG010100
00262           IF(AMAX-1.) 215,215,230                   DG010200
00265       215 NTRY= 1                                   DG010300
00266           CALL CNTRL(Y,DY,DEL,T,NTRY,IFVD)          DG010400
00267       300 IF(NTRY-1) 185,185,310                    DG010500
00272       310 IF(NTRY-2) 270,270,330                    DG010600
00275       330 IF(NTRY-3) 340,340,5                      DG010700
00300       340 T=T-DDT                                   DG010800
00301           IF(DEL) 259,10,259                        DG010900
00304       185 GO TO (40,190),ISYMP                      DG011000
00305       190 IF(AMAX-.75) 200,25,220                   DG011100
00310       200 IF(AMAX-.075) 210,25,25                   DG011200
00313       210 DEL=DEL*FR10                              DG011300
00314           GO TO 25                                  DG011400
00315       220 DEL=DEL/FR10                              DG011500
00316           GO TO 25                                  DG011600
00317       230 I =1+ IBKP                                DG011700
00320           GO TO (240,250),I                         DG011800
00321       240 T=T-DEL                                   DG011900
00322           DEL=DEL/FR10                              DG012000
00323           GO TO  259                                DG012100
00324       250 J=1                                       DG012200
00325       251 AM=AMAX/10.**J                            DG012300
00326           IF(1.-AM) 255,257,257                     DG012400
00331       255 J=J+1                                     DG012500
00332           GO TO 251                                 DG012600
00333       257 T=T-DEL                                   DG012700
00334           DEL=DEL/(FR10**J)                         DG012800
00335       259 DO 245 I=1,N                              DG012900
00340           DY(I)=DYST(I)                             DG013000
00341       245 Y(I)=YST(I)                               DG013100
00343           GO TO 25                                  DG013200
00344       270 RETURN                                    DG013300
00345           END                                       DG013400
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****** RKSF ******

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END OF COMPILATION: NO DIAGNOSTICS.

@HDG,P ****** SHADE ****** .

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****** SHADE ******                                                          DATE 071372        PAGE    1

@FOR,S ME*NASA5.SHADE,ME*NASA5.SHADE
FOR S9A-07/13/72-20:58:04 (0,)

   SUBROUTINE SHADE      ENTRY POINT 000073

   STORAGE USED: CODE(1) 000104; DATA(0) 000023; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001    000027 10L       0001    000015 106G      0001    000057 123G      0000    000005 INJP$     0000 I 000001 J
    0000 I 000003 J1         0000 I 000002 J2         0000 R 000000 QM


00101                    SUBROUTINE SHADE(Q,NS)
00103                    DIMENSION Q(1)
00104                    QM = 0.0
00105                    DO 10 J = 1,NS
00110                    IF (QM.GT.Q(J)) GO TO 10
00112                    QM = Q(J)
00113                    J2 = J
00114           10       CONTINUE
00116                    J1 = 1
00117                    IF (J2.LE.NS/2) J1 = NS/2+1
00121                    J2 = J1+NS/2-1
00122                    DO 20 J = J1,J2
00125           20       Q(J) = 0.0
00127                    RETURN
00130                    END

      END OF COMPILATION:        NO  DIAGNOSTICS.

 @HDG,P  ******  SHAPEF  ******
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```
@FOR,S ME*NASA5.SHAPEF,ME*NASA5.SHAPEF
FOR S9A-07/13/72-20:58:06 (0,)

   SUBROUTINE SHAPEF     ENTRY POINT 001020

   STORAGE USED: CODE(1) 001035; DATA(0) 000152; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003    QRD     003721
    0004    SSF     000010

   EXTERNAL REFERENCES (BLOCK, NAME)

    0005    ACOS
    0006    ATAN
    0007    SQRT
    0010    COS
    0011    SIN
    0012    NEXP6$
    0013    ASIN
    0014    ALOG
    0015    NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001    000036 117G     0001    000037 122G     0001    000040 125G     0001    000066 135G     0001    000307 174G
    0001    000053 20L      0001    000447 216G     0001    000452 221G     0001    000457 225G     0001    000671 261G
    0001    000752 274G     0001    000107 30L      0001    000757 300G     0001    000115 35L      0001    000603 62L
    0001    000620 64L      0001    000634 65L      0001    000442 70L      0000 R  000046 A        0004 R  000002 ALPFN
    0000 R  000047 AR       0000 R  000050 ARC      0000 R  000051 AR2      0000 R  000035 BA       0000 R  000027 BETA
    0000 R  000066 BETA1    0000 R  000067 BETA2    0000 R  000014 CF       0000 R  000043 CPB      0003 R  003465 CSF
    0000 R  000015 DCL      0003    003464 DXX2     0003    003472 DXX21    0000 R  000064 DZ       0003 R  003463 DZMFN
    0000 R  000045 DZ2      0003    003410 EBFN     0003    003441 EBMP     0003    003467 EXTIFN   0003    003471 EXTIMP
    0003    003466 EXTSFN   0003    003470 EXTSMP   0000 R  000062 GAMA     0000 R  000036 GAMMA    0000 I  000021 I
    0000    000112 INJP$    0000 I  000022 J        0000 I  000023 K        0000 I  000024 L        0003    003461 LCT
    0003    003462 LTT      0000 I  000052 M        0003    003460 MCVRD    0000 R  000032 OB       0000 R  000034 OP
    0000 R  000033 PB       0000 R  000017 PHI      0000 R  000037 PHI0     0000 R  000055 PHI1     0000 R  000012 PI
    0000 R  000013 PI2      0000 R  000040 PR4      0000 R  000044 RC       0000 R  000031 RHO      0000 R  000030 RHO2
    0000 R  000053 RL       0000 R  000057 RL2      0000 R  000016 RR       0000 R  000041 RRO      0000 R  000042 RRO2
    0000 R  000054 RT       0000 R  000061 RTL      0000 R  000056 RT2      0004 R  000003 R1       0004 R  000000 R2
    0003 R  003473 SS       0000 R  000063 SST      0003 R  003670 SSTT     0004 R  000001 T        0000 R  000020 THETA
    0000 R  000060 THETA1   0003    000000 TRMTX    0000 R  000070 WF       0004 R  000006 WWA      0004 R  000007 WWB
    0000 R  000000 X        0000 R  000065 XB       0004 R  000005 XSMP     0004    000004 XSPM     0000 R  000005 XX
    0003 R  003446 XX2      0000 R  000025 Y        0000 R  000026 YY       0003 R  003453 ZZ2


00101      1*           SUBROUTINE   SHAPEF
00101      2*      C
00101      3*      C    THIS SUBROUTINE COMPUTES THE SHAPE FACTOR BETWEEN :
00101      4*      C      1- TUBE AND NEAR FIN
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00101          C       1- TUBE AND FAR FIN
00101          C       3- ADJACENT TUBES
00101          C
00103                  COMMON /QRD/ TRMTX(30,60),EBFN(5,5),EBMP(5),XX2(5),ZZ2(5),
00103                1              MCVRD,LCT,LTT,DZMFN,
00103                2              DXX2,CSF,EXTSFN,EXTIFN,EXTSMP,EXTIMP,DXX21,SS(5,5,5)
00103                3              ,SSTT(5,5)
00104                  COMMON /SSF/R2, T, ALPFN,R1,XSPM,XSMP,WWA,WWB
00105                  DIMENSION X(5), XX(5)
00106                  PI     = 3.14159
00107                  PI2    = PI/2.0
00110                  CF     = DZMFN*4.0
00111                  DCL    = 2.0+2.0*R1
00112                  RR     = R2*R2
00113                  PHI    = ACOS((XSMP+R1)/R2)
00114                  THETA  =1.570796-PHI
00115                  CSF    = 1.0/(R2*THETA)
00116                  DO 10 I=1,5
00121                  DO 10 J=1,5
00124                  DO 10 K=1,5
00127               10 SS(I,J,K) = 0.0
00133                  L      = 0
00134               20 DO  50 I=1,5
00137                  IF (L.EQ.1) GO TO 30
00141                  X(I)   = XX2(I)+R1
00142                  XX(I)  = XX2(I)
00143                  Y      = WWA*X(I)+WWB
00144                  YY     = Y*Y
00145                  IF (L.EQ.0) GO TO 35
00147               30 X(I)   = DCL-X(I)
00150                  XX(I)  = 2.0-XX2(I)
00151               35 BETA   = ATAN(Y/X(I))
00152                  RHO2   = X(I)*X(I)+YY
00153                  RHO    = SQRT(RHO2)
00154                  OB     = ACOS(R2/RHO)
00155                  PB     = PHI-BETA
00156                  OP     = OB-PB
00157                  BA     = BETA+ALPFN
00160                  GAMMA  = OB+BA
00161                  IF (L.EQ.1) BA = BETA-ALPFN
00163                  PHIO   = ATAN(DZMFN/(2.0*XX(I)))
00164                  SS(I,1,1) = ((1.0-SIN(GAMMA))/PI)*(PHIO+SIN(2.0*PHIO)/2.0)*4.0+
00164                1              SS(I,1,1)
00165                  PR4    = 4.*PI*RHO
00166                  RRO    = 2.*R2*RHO
00167                  RRO2   = RRO*RRO
00170                  CPB    = COS(PB)
00171                  RC     = RRO*CPB
00172                  J      = 1
00173                  DO 50 K=2,5
00176                  DZ2    = ((ZZ2(K)-ZZ2(J))*CF)**2
00177                  A      = RR+RHO2+DZ2
00200                  AR     = A*A-RRO2
00201                  ARC    = A-RC
00202                  AR2    = A-2.0*RR
00203                  SS(I,J,K) = (COS(BA)/PR4*(ALOG(ARC/AR2)-1.0+AR2/ARC)+SIN(BA)/PR4*
00203                1              (OP+(2.0*RRO2*DZ2-A*AR)/(AR**1.5)*(ASIN((RRO-A*COS(OB)
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00203              2              )/AR2)-ASIN((RRO-A*CPB)/ARC))+(4.0*A*DZ2/AR-2.0)*((R2
00203              3              *RHO*SIN(OB))/AR2-(R2*RHO*SIN(PB))/ARC)))*CF+SS(I,J,K)
00204                 IF (SS(I,J,K) .LT. 0.0) SS(I,J,K) = 0.0
00206              50 CONTINUE
00211                 IF (L.EQ.1) GO TO 70
00213                 L       = 1
00214                 GO TO 20
00215              70 DO 60 I=1,5
00220                 DO 60 K=2,5
00223                 SS(I,K,1) = SS(I,1,K)
00224                 DO 60 J=2,5
00227                 M       = ABS(J-K)+1
00230              60 SS(I,J,K) = SS(I,1,M)
00234                 RL      = DCL/R2-COS(PHI)
00235                 RT      = T/R2
00236                 PHI1    = ATAN(RT/RL)
00237                 RT2     = RT*RT
00240                 RL2     = RL*RL
00241                 THETA1  = ACOS(1.0/SQRT(RT2+RL2))
00242                 RTL     = (1.0-RT2)/RL2
00243                 GAMA    = PI2-PHI1-THETA1
00244                 IF (RTL-1.0E-03) 62,62,61
00247              61 SST     = (GAMA+RL*(SQRT(1.0-RTL)-1.0))/(PI2-PHI)
00250                 GO TO 65
00251              62 IF(RTL-1.0E-04) 63,64,64
00254              63 SST     = (GAMA-RL*RTL/2.0)/(PI2-PHI)
00255                 GO TO 65
00256              64 SST     = (GAMA-RL*(RTL/2.0+RTL*RTL/8.0))/(PI2-PHI)
00257              65 J       = 1
00260                 DO 80 K=1,5
00263                 DZ      = (ZZ2(K)-ZZ2(J))*CF
00264                 XB      = 2.0*(1.0+R1-R2*COS((PHI1+THETA1)/2.0))
00265                 BETA1   = ATAN((DZ-DZMFN/2.0)/XB)
00266                 BETA2   = ATAN((DZ+DZMFN/2.0)/XB)
00267                 WF      = (BETA2-BETA1)/2.0+(SIN(2.0*BETA2)-SIN(2.0*BETA1))/4.0
00270                 SSTT(J,K) = 8.0*SST*WF/PI
00271              80 CONTINUE
00273                 DO 90 K=2,5
00276                 SSTT(K,1) = SSTT(1,K)
00277                 DO 90 J=2,5
00302                 M       = ABS(J-K)+1
00303              90 SSTT(J,K) = SSTT(1,M)
00306                 RETURN
00307                 END

        END OF COMPILATION:        NO  DIAGNOSTICS.


QHDG,P  ******  TCALC  ******
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```
@FOR,S ME*NASA5.TCALC,ME*NASA5.TCALC
FOR S9A-07/13/72-20:58:10 (0,)

   SUBROUTINE TCALC      ENTRY POINT 000635

   STORAGE USED: CODE(1) 000652; DATA(0) 000670; BLANK COMMON(2) 000000

    COMMON BLOCKS:

     0003   ADBH    000352
     0004   TC      000042
     0005   QIN     001610

   EXTERNAL REFERENCES (BLOCK, NAME)

     0006   YINT
     0007   SHADE
     0010   NRBU$
     0011   NIO2$
     0012   NBSP$
     0013   NIO1$
     0014   NEXP6$
     0015   NREW$
     0016   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

     0001   000024 10L      0001   000426 110L     0001   000024 125G     0001   000047 141G     0001   000121 160G
     0001   000127 165G     0001   000146 173G     0001   000164 203G     0001   000247 220G     0001   000252 223G
     0001   000276 232G     0001   000504 261G     0001   000042 30L      0001   000070 50L      0001   000254 90L
     0004 R 000003 ABEMF    0003   000001 AL       0000 R 000562 ANG      0003   000161 CONFL    0003   000173 CONFNA
     0003   000147 CP       0003   000000 D        0003   000326 DTL      0003   000244 EFF      0003   000205 EMIS
     0003   000013 H        0000 R 000623 HA       0003   000231 HAB      0000 R 000624 HP       0000 R 000622 HS
     0000 I 000611 I        0004 I 000001 ICASE    0000   000637 INJP$    0000 I 000614 ISYM     0004 I 000000 ITAPE
     0000 I 000615 IJ       0000 I 000613 IUL      0000 I 000612 J        0000 I 000616 J1       0000 I 000617 J2
     0000 I 000621 K        0003 R 000064 M        0000 I 000610 NS       0005 I 001605 NSRD     0003   000076 NT
     0005 I 001604 NTF      0000 R 000620 PANG     0004 R 000004 PHIN     0003   000052 PIN      0000 R 000436 QA
     0000 R 000124 QALB     0005   000454 QIFN     0005   001274 QITB     0003   000314 QOUT     0000 R 000510 QP
     0000 R 000244 QPLN     0000 R 000364 QS       0005   000144 QSFN     0005   000764 QSTB     0000 R 000004 QSUN
     0005   001606 QTO      0000 R 000607 STFBOL   0003   000217 TB       0003   000026 TH       0000 R 000000 TIM
     0003   000040 TIN      0003   000270 TL       0005   000000 TM       0004 R 000002 TO       0003   000340 TOUT
     0003 R 000077 TSTAR    0005   001607 TX       0003   000135 VSC      0006 R 000000 YINT


                         SUBROUTINE TCALC(NTF)
                         PARAMETER NTP = 10
                         PARAMETER MAXSID = 20
                         PARAMETER NTP1 = NTP+1
                         PARAMETER MAXSD1 = MAXSID+1
                         REAL M
                         COMMON /ADBH/ D,AL(NTP),H(NTP1),TH(NTP),TIN(NTP),PIN(NTP),
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     1 M(NTP),NT,TSTAR(NTP,3),VSC(NTP),CP(NTP),CONFL(NTP),
     2 CONFNA(NTP),EMIS(NTP),TB(NTP),HAB(NTP1),EFF(NTP,2),TL(NTP,2),
     3 QOUT(NTP),DTL(NTP),TOUT(NTP)
       COMMON /TC/ ITAPE,ICASE,TO,ABEMF,PHIN(NTP,3)
       COMMON /QIN/ TM(100),QSFN(100,2),QIFN(100,2),QSTB(100,2),
     1 QITB(100,2),NTM,NSRD,QTO,TX
       DIMENSION TIM(4),QSUN(4,MAXSID),QALB(4,MAXSID),QPLN(4,MAXSID),
     1 QS(MAXSD1,2),QA(MAXSD1,2),QP(MAXSD1,2),ANG(MAXSD1)
       DATA STFBOL/0.1714E-8/
       READ (ITAPE) NS,TIM(1)
       IF (ICASE.LE.1) GO TO 30
       DO 20 I = 2,ICASE
 10    TIM(2) = TIM(1)
       READ (ITAPE) NS,TIM(1)
       IF (TIM(1).GT.TIM(2)) GO TO 10
 20    CONTINUE
 30    DO 40 J = 0,NS
 40    ANG(J+1) = FLOAT(J*360+180)/NS
       READ (ITAPE)
       I = 2
 50    READ (ITAPE) NS,TIM(1)
       I = I+1
       IF (TIM(1).LT.TO.AND.I.LT.NTM-1) GO TO 50
       DO 60 I = 1,3
 60    BACKSPACE ITAPE
       DO 70 I = 1,4
 70    READ (ITAPE) NS,TIM(I),(QSUN(I,J),QALB(I,J),QPLN(I,J),J=1,NS)
       DO 80 J = 1,NS
       QS(J,1) = YINT(TIM,QSUN(1,J),4,4,TO)
       QA(J,1) = YINT(TIM,QALB(1,J),4,4,TO)
 80    QP(J,1) = YINT(TIM,QPLN(1,J),4,4,TO)
       QS(NS+1,1) = QS(1,1)
       QA(NS+1,1) = QA(1,1)
       QP(NS+1,1) = QP(1,1)
       IUL = 1
       IF (ISYM.EQ.3) IUL = 3
       DO 120 IU = 1,IUL
       DO 120 I = 1,NTF
       J1 = 0
 90    J1 = J1+1
       IF (ANG(J1)+ANG(1).LE.PHIN(I,IU)) GO TO 90
       DO 100 J = 1,NS
       J2 = MIN(MAX(MOD(J+J1-2,NS),1),NS-2)
       PANG = ANG(J)+PHIN(I,IU)
       IF (PANG.GE.ANG(NS+1)) PANG = PANG-360.0
       QS(J,2) = YINT(ANG(J2),QS(J2,1),4,4,PANG)
       QA(J,2) = YINT(ANG(J2),QA(J2,1),4,4,PANG)
 100   QP(J,2) = YINT(ANG(J2),QP(J2,1),4,4,PANG)
       CALL SHADE(QS(1,2),NS)
       CALL SHADE(QA(1,2),NS)
       CALL SHADE(QP(1,2),NS)
       PANG = AMOD(PHIN(I,IU)+90.0,360.0)
       J1 = 0
 110   J1 = J1+1
       IF (ANG(J1).LE.PANG) GO TO 110
       J2 = 0
       IF (PANG.GE.180.0) J2 = NS/2
```

```
00257                 K = J2+MIN(MAX(J1-J2-2,1),NS/2-3)
00260                 DO 120 J = IU,NSRD
00263                 IF (J.NE.IU) K = MOD(K+NS/2,NS)
00265                 HS = YINT(ANG(K),QS(K,2),4,4,PANG)
00266                 HA = YINT(ANG(K),QA(K,2),4,4,PANG)
00267                 HP = YINT(ANG(K),QP(K,2),4,4,PANG)
00270         120     TSTAR(I,J) = ((HP+(HA+HS)*ABEMF)/STFBOL)**0.25
00274                 REWIND ITAPE
00275                 RETURN
00276                 END

      END OF COMPILATION:       NO  DIAGNOSTICS.


QHDG,P  ******  THCF/CFFC43  ******
```

```
@FOR,S ME*NASA5.THCF/CFFC43,ME*NASA5.THCF/CFFC43
FOR S9A-07/13/72-20:58:14 (0,)

   FUNCTION THCF        ENTRY POINT 000013

   STORAGE USED: CODE(1) 000015; DATA(0) 000010; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000003 INJP$     0000 R 000000 THCF      0000 R 000001 X1       0000 R 000002 X2


 00101      1*          FUNCTION THCF(RHO,T)
 00101      2*     C
 00101      3*     C       THIS FUNCTION SUBPROGRAM COMPUTES :
 00101      4*     C       THERMAL CONDUCTIVITY AS A FUNCTION OF DENSITY (SLUG/CU.FT)
 00101      5*     C            AND TEMPERATURE (R) OF FC-43
 00101      6*     C                                 UNITS BTU/(HR.FT.R)
 00101      7*     C
 00103      8*          DATA X1,X2 /0.061442,-2.5E-05/
 00106      9*          THCF = X1+X2*T
 00107     10*          RETURN
 00110     11*          END

      END OF COMPILATION:        NO  DIAGNOSTICS.


 @HDG,P  ******  THCF/CFFC75  ******
```

```
******  THCF/CFFC75  ******                                                                    DATE 071372        PAGE     1

@FOR,S ME*NASA5.THCF/CFFC75,ME*NASA5.THCF/CFFC75
FOR S9A-07/13/72-20:58:16 (0,)

   FUNCTION THCF        ENTRY POINT 000013

   STORAGE USED: CODE(1) 000015; DATA(0) 000010; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000003 INJP$     0000 R 000000 THCF      0000 R 000001 X1        0000 R 000002 X2


00101          FUNCTION THCF(RHO,T)
00101     C
00101     C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101     C       THERMAL CONDUCTIVITY AS A FUNCTION OF DENSITY (SLUG/CU.FT)
00101     C            AND TEMPERATURE (R) OF FC-75
00101     C                                             UNITS BTU/(HR.FT.R)
00101     C
00103          DATA X1,X2 /0.114181,-6.53E-05/
00106          THCF = X1+X2*T
00107          RETURN
00110          END

      END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  THCF/CFHE  ******
```

```
@FOR,S ME*NASA5.THCF/CFHE,ME*NASA5.THCF/CFHE
FOR S9A-07/13/72-20:58:18 (0,)

   FUNCTION THCF        ENTRY POINT 000022

   STORAGE USED: CODE(1) 000024; DATA(0) 000015; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000006 DT        0000   000010 INJP$     0000 R 000000 THCF      0000 R 000007 THETA     0000 R 000005 TO
    0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3        0000 R 000004 X4


00101                FUNCTION THCF(RHO,T)
00101           C
00101           C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101           C        THERMAL CONDUCTIVITY AS A FUNCTION OF DENSITY (SLUG/CU.FT)
00101           C             AND TEMPERATURE (R) OF HELIUM
00101           C                                         UNITS BTU/(HR.FT.R)
00101           C
00103                DATA X1,X2,X3,X4 /0.0404,0.0302,-0.0033,0.0003/,TO,DT /160.0,20
00103               10.0/
00112                THETA = (T-TO)/DT
00113                THCF  = ((X4*THETA+X3)*THETA+X2)*THETA+X1
00114                RETURN
00115                END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  THCF/CFNAK  ******
```

```
@FOR,S ME*NASA5.THCF/CFNAK,ME*NASA5.THCF/CFNAK
FOR S9A-07/13/72-20:58:20 (0,)

   FUNCTION THCF        ENTRY POINT 000024

   STORAGE USED: CODE(1) 000026; DATA(0) 000016; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000007 DT        0000   000011 INJP$     0000 R 000000 THCF      0000 R 000010 THETA     0000 R 000006 T0
    0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3        0000 R 000004 X4        0000 R 000005 X5


00101           FUNCTION THCF(RHO,T)
00101      C
00101      C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101      C       THERMAL CONDUCTIVITY AS A FUNCTION OF DENSITY (SLUG/CU.FT)
00101      C            AND TEMPERATURE (R) OF NAK 78.6
00101      C                                    UNITS BTU/(HR.FT.R)
00101      C
00103           DATA X1,X2,X3,X4,X5 /13.36,1.414167,-0.142083,-0.069167,0.007083/,
00103          1T0,DT /659.67,300.0/
00113           THETA = (T-T0)/DT
00114           THCF  = (((X5*THETA+X4)*THETA+X3)*THETA+X2)*THETA+X1
00115           RETURN
00116           END
        END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  THCF/CFSIL  ******
```

```
@FOR,S ME*NASA5.THCF/CFSIL,ME*NASA5.THCF/CFSIL
FOR S9A-07/13/72-20:58:22 (0,)

   FUNCTION THCF        ENTRY POINT 000043

   STORAGE USED: CODE(1) 000047; DATA(0) 000031; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NIO2$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000003 1F        0000   000023 INJP$     0000 R 000000 THCF      0000 R 000001 X1       0000 R 000002 X2


00101              FUNCTION THCF(RHO,T)
00101        C
00101        C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101        C        THERMAL CONDUCTIVITY AS A FUNCTION OF DENSITY (SLUG/CU.FT) AND
00101        C              TEMPERATURE (R) OF DOW CORNING 200 SILICON OIL (1 CS)
00101        C                                       UNITS BTU/(HR.FT.R)
00101        C              TEMPERATURE .GE. 359.67 AND .LE. 859.67
00101        C
00103              DATA X1,X2 /0.070052,-2.2105E-05/
00106              THCF = X1+X2*T
00107              IF (T.GE.359.67.AND.T.LE.859.67) RETURN
00111              WRITE (6,1) T
00114            1 FORMAT (1H0,61HTHERMAL CONDUCTIVITY OF SILICON OIL, TEMP. OUT OF R
00114             1ANGE, T = ,F8.3,/)
00115              RETURN
00116              END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ****** THCFN/FNAL  ******
```

```
******  THCFN/FNAL  ******                                                         DATE 071372        PAGE      1

@FOR,S ME*NASA5.THCFN/FNAL,ME*NASA5.THCFN/FNAL
FOR S9A-07/13/72-20:58:25 (0,)

   FUNCTION THCFN       ENTRY POINT 000054

   STORAGE USED: CODE(1) 000060; DATA(0) 000037; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000011 1F       0000 R 000007 DT       0000   000031 INJP$     0000 R 000000 THCFN     0000 R 000010 THETA
    0000 R 000006 T0       0000 R 000001 X1       0000 R 000002 X2       0000 R 000003 X3        0000 R 000004 X4
    0000 R 000005 X5

00101      1*             FUNCTION THCFN(T)
00101      2*      C
00101      3*      C         THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*      C       THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE (R) OF
00101      5*      C              ALUIMINUM 7075
00101      6*      C                                         UNITS BTU/(HR.FT.R)
00101      7*      C              TEMP. GE. 300.0.AND.LE. 1200.0 R
00101      8*      C
00103      9*             DATA X1,X2,X3,X4,X5 /88.5,13.0665,0.33275,-1.758,0.25375/,T0,DT /
00103     10*            1400.0,200.0/
00113     11*             THETA = (T-T0)/DT
00114     12*             THCFN = (((X5*THETA+X4)*THETA+X3)*THETA+X2)*THETA+X1
00115     13*             IF (T.GE.300.0.AND.T.LE.1200.0) RETURN
00117     14*             WRITE (6,1) T
00122     15*           1 FORMAT (1H0,58HTHERMAL CONDUCTIVITY OF ALUMINUM, TEMP. OUT OF RANG
00122     16*            1E, T = ,F8.3,/)
00123     17*             RETURN
00124     18*             END

      END OF COMPILATION:        NO  DIAGNOSTICS.

@HDG,P  ******  THCFN/FNBR  ******
```

```
****** THCFN/FNBR ******                                                              DATE 071372        PAGE      1

 @FOR,S ME*NASA5.THCFN/FNBR,ME*NASA5.THCFN/FNBR
 FOR S9A-07/13/72-20:58:27 (0,)

    FUNCTION THCFN        ENTRY POINT 000054

    STORAGE USED: CODE(1) 000060; DATA(0) 000037; BLANK COMMON(2) 000000

    EXTERNAL REFERENCES (BLOCK, NAME)

     0003   NWDU$
     0004   NI02$
     0005   NERR3$

    STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

     0000   000011 1F       0000 R 000007 DT       0000   000031 INJP$     0000 R 000000 THCFN     0000 R 000010 THETA
     0000 R 000006 T0       0000 R 000001 X1       0000 R 000002 X2      0000 R 000003 X3      0000 R 000004 X4
     0000 R 000005 X5

 00101      1*          FUNCTION THCFN(T)
 00101      2*     C
 00101      3*     C        THIS FUNCTION SUBPROGRAM COMPUTES :
 00101      4*     C        THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE (R) OF
 00101      5*     C              BERYLIUM WITH 0.84-1.68 DEO
 00101      6*     C                                         UNITS BTU/(HR.FT.R)
 00101      7*     C              TEMP. GE. 400.0 AND LE. 1700.0 R
 00101      8*     C
 00103      9*          DATA X1,X2,X3,X4,X5 /108.863,-10.5643,0.82683,-0.20167,0.020167/,
 00103     10*         1T0,DT /400.0,200.0/
 00113     11*          THETA = (T-T0)/DT
 00114     12*          THCFN = (((X5*THETA+X4)*THETA+X3)*THETA+X2)*THETA+X1
 00115     13*          IF (T.GE.400.0.AND.T.LE.1700.0) RETURN
 00117     14*          WRITE (6,1) T
 00122     15*        1 FORMAT (1H0,58HTHERMAL CONDUCTIVITY OF BERYLIUM, TEMP. OUT OF RANG
 00122     16*         1E, T = ,F8.3,/)
 00123     17*          RETURN
 00124     18*          END

       END OF COMPILATION:        NO  DIAGNOSTICS.

 @HDG,P  ****** THCFN/FNCU ******
```

```
@FOR,S ME*NASA5.THCFN/FNCU,ME*NASA5.THCFN/FNCU
FOR S9A-07/13/72-20:58:29 (0,)

   FUNCTION THCFN       ENTRY POINT 000051

   STORAGE USED: CODE(1) 000055; DATA(0) 000034; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000007 1F        0000 R 000005 DT        0000   000026 INJP$     0000 R 000000 THCFN     0000 R 000006 THETA
    0000 R 000004 TO        0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3


00101      1*          FUNCTION THCFN(T)
00101      2*     C
00101      3*     C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*     C       THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE (R) OF COPPER
00101      5*     C                             UNITS BTU/(HR.FT.R)
00101      6*     C            TEMP. GE. 500.0 AND LE. 1800.0 R
00101      7*     C
00103      8*          DATA X1,X2,X3 /228.369,-2.62067,-0.04033/,TO,DT /600.0,200.0/
00111      9*          THETA = (T-TO)/DT
00112     10*          THCFN = (X3*THETA*THETA+X2)*THETA+X1
00113     11*          IF (T.GE.500.0.AND.T.LE.1800.0) RETURN
00115     12*          WRITE (6,1) T
00120     13*        1 FORMAT (1H0,56HTHERMAL CONDUCTIVITY OF COPPER, TEMP. OUT OF RANGE,
00120     14*         1 T = ,F8.3,/)
00121     15*          RETURN
00122     16*          END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ****** THCMP/MPAL  ******
```

```
@FOR,S ME*NASA5.THCMP/MPAL,ME*NASA5.THCMP/MPAL
FOR S9A-07/13/72-20:58:31 (0,)

   FUNCTION THCMP        ENTRY POINT 000054

   STORAGE USED: CODE(1) 000060; DATA(0) 000037; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000011 1F        0000 R 000007 DT        0000   000031 INJP$      0000 R 000000 THCMP      0000 R 000010 THETA
    0000 R 000006 T0        0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3         0000 R 000004 X4
    0000 R 000005 X5


 00101      1*           FUNCTION THCMP(T)
 00101      2*      C
 00101      3*      C       THIS FUNCTION SUBPROGRAM COMPUTES :
 00101      4*      C     THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE (R) OF
 00101      5*      C            ALUIMINUM 7075
 00101      6*      C                                UNITS BTU/(HR.FT.R)
 00101      7*      C            TEMP. GE. 300.0.AND.LE. 1200.0 R
 00101      8*      C
 00103      9*           DATA X1,X2,X3,X4,X5 /88.5,13.0665,0.33275,-1.758,0.25375/,T0,DT /
 00103     10*          1400.0,200.0/
 00113     11*           THETA = (T-T0)/DT
 00114     12*           THCMP = (((X5*THETA+X4)*THETA+X3)*THETA+X2)*THETA+X1
 00115     13*           IF (T.GE.300.0.AND.T.LE.1200.0) RETURN
 00117     14*           WRITE (6,1) T
 00122     15*         1 FORMAT (1H0,58HTHERMAL CONDUCTIVITY OF ALUMINUM, TEMP. OUT OF RANG
 00122     16*          1E, T = ,F8.3,/)
 00123     17*           RETURN
 00124     18*           END

      END OF COMPILATION:        NO  DIAGNOSTICS.


 @HDG,P  ******  THCMP/MPBR  ******
```

```
@FOR,S ME*NASA5.THCMP/MPBR,ME*NASA5.THCMP/MPBR
FOR S9A-07/13/72-20:58:34 (0,)

   FUNCTION THCMP       ENTRY POINT 000054

   STORAGE USED: CODE(1) 000060; DATA(0) 000037; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000011 1F       0000 R 000007 DT       0000   000031 INJP$     0000 R 000000 THCMP     0000 R 000010 THETA
    0000 R 000006 T0       0000 R 000001 X1       0000 R 000002 X2       0000 R 000003 X3       0000 R 000004 X4
    0000 R 000005 X5


00101            FUNCTION THCMP(T)
00101      C
00101      C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101      C        THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE (R) OF
00101      C             BERYLIUM WITH 0.84-1.68 BEO
00101      C                                        UNITS BTU/(HR.FT.R)
00101      C             TEMP. GE. 400.0 AND LE. 1700.0 R
00101      C
00103            DATA X1,X2,X3,X4,X5 /108.863,-10.5643,0.82683,-0.20167,0.020167/,
00103           1T0,DT /400.0,200.0/
00113            THETA = (T-T0)/DT
00114            THCMP = (((X5*THETA+X4)*THETA+X3)*THETA+X2)*THETA+X1
00115            IF (T.GE.400.0.AND.T.LE.1700.0) RETURN
00117            WRITE (6,1) T
00122          1 FORMAT (1H0,58HTHERMAL CONDUCTIVITY OF BERYLIUM, TEMP. OUT OF RANG
00122           1E, T = ,F8.3,/)
00123            RETURN
00124            END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  THCMP/MPCU  ******
```

```
@FOR,S ME*NASA5.THCMP/MPCU,ME*NASA5.THCMP/MPCU
FOR S9A-07/13/72-20:58:36 (0,)

   FUNCTION THCMP       ENTRY POINT 000051

   STORAGE USED: CODE(1) 000055; DATA(0) 000034; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000    000007 1F        0000 R 000005 DT        0000    000026 INJP$      0000 R 000000 THCMP      0000 R 000006 THETA
    0000 R 000004 T0        0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3


00101              FUNCTION THCMP(T)
00101        C
00101        C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101        C        THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE (R) OF COPPER
00101        C                                   UNITS BTU/(HR.FT.R)
00101        C             TEMP. GE. 500.0 AND LE. 1800.0 R
00101        C
00103              DATA X1,X2,X3 /228.369,-2.62067,-0.04033/,T0,DT /600.0,200.0/
00111              THETA = (T-T0)/DT
00112              THCMP = (X3*THETA*THETA+X2)*THETA+X1
00113              IF (T.GE.500.0.AND.T.LE.1800.0) RETURN
00115              WRITE (6,1) T
00120            1 FORMAT (1H0,56HTHERMAL CONDUCTIVITY OF COPPER, TEMP. OUT OF RANGE,
00120             1 T = ,F8.3,/)
00121              RETURN
00122              END

      END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  THCTB/TBAL  ******
```

```
@FOR,S ME*NASA5.THCTB/TBAL,ME*NASA5.THCTB/TBAL
FOR S9A-07/13/72-20:58:40 (0,)

   FUNCTION THCTB       ENTRY POINT 000054

   STORAGE USED: CODE(1) 000060; DATA(0) 000037; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NIO2$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000    000011 1F       0000 R 000007 DT      0000    000031 INJP$    0000 R 000000 THCTB    0000 R 000010 THETA
    0000 R 000006 T0        0000 R 000001 X1      0000 R 000002 X2        0000 R 000003 X3       0000 R 000004 X4
    0000 R 000005 X5


00101          FUNCTION THCTB(T)
00101     C
00101     C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101     C     THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE (R) OF
00101     C            ALUMINUM 7075
00101     C                                  UNITS BTU/(HR.FT.R)
00101     C            TEMP. GE. 300.0.AND.LE. 1200.0 R
00101     C
00103          DATA X1,X2,X3,X4,X5 /88.5,13.0665,0.33275,-1.758,0.25375/,T0,DT /
00103         1400.0,200.0/
00113          THETA = (T-T0)/DT
00114          THCTB = (((X5*THETA+X4)*THETA+X3)*THETA+X2)*THETA+X1
00115          IF (T.GE.300.0.AND.T.LE.1200.0) RETURN
00117          WRITE (6,1) T
00122        1 FORMAT (1H0,58HTHERMAL CONDUCTIVITY OF ALUMINUM, TEMP. OUT OF RANG
00122         1E, T = ,F8.3,/)
00123          RETURN
00124          END

      END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  THCTB/TBBR  ******
```

```
******  THCTB/TBBR  ******                                                              DATE 071372        PAGE      1

@FOR,S ME*NASA5.THCTB/TBBR,ME*NASA5.THCTB/TBBR
FOR S9A-07/13/72-20:58:42 (0,)

   FUNCTION THCTB       ENTRY POINT 000054

   STORAGE USED: CODE(1) 000060; DATA(0) 000037; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NIO2$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000011 1F        0000 R 000007 DT        0000   000031 INJP$      0000 R 000000 THCTB      0000 R 000010 THETA
    0000 R 000006 T0        0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3         0000 R 000004 X4
    0000 R 000005 X5


00101      1*          FUNCTION THCTB(T)
00101      2*     C
00101      3*     C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*     C       THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE (R) OF
00101      5*     C            BERYLIUM WITH 0.84-1.68 BEO
00101      6*     C                                        UNITS BTU/(HR.FT.R)
00101      7*     C            TEMP. GE. 400.0 AND LE. 1700.0 R
00101      8*     C
00103      9*          DATA X1,X2,X3,X4,X5 /108.863,-10.5643,0.82683,-0.20167,0.020167/,
00103     10*         1T0,DT /400.0,200.0/
00113     11*          THETA = (T-T0)/DT
00114     12*          THCTB = (((X5*THETA+X4)*THETA+X3)*THETA+X2)*THETA+X1
00115     13*          IF (T.GE.400.0.AND.T.LE.1700.0) RETURN
00117     14*          WRITE (6,1) T
00122     15*        1 FORMAT (1H0,58HTHERMAL CONDUCTIVITY OF BERYLIUM, TEMP. OUT OF RANG
00122     16*         1E, T = ,F8.3,/)
00123     17*          RETURN
00124     18*          END

       END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  THCTB/TBCU  ******
```

```
@FOR,S ME*NASA5.THCTB/TBCU,ME*NASA5.THCTB/TBCU
FOR S9A-07/13/72-20:58:44 (0,)

   FUNCTION THCTB       ENTRY POINT 000051

   STORAGE USED: CODE(1) 000055; DATA(0) 000034; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NI02$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   000007 1F        0000 R 000005 DT        0000   000026 INJP$      0000 R 000000 THCTB      0000 R 000006 THETA
    0000 R 000004 T0        0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3


00101          FUNCTION THCTB(T)
00101     C
00101     C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101     C       THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE (R) OF COPPER
00101     C                                        UNITS BTU/(HR.FT.R)
00101     C            TEMP. GE. 500.0 AND LE. 1800.0 R
00101     C
00103          DATA X1,X2,X3 /228.369,-2.62067,-0.04033/,T0,DT /600.0,200.0/
00111          THETA = (T-T0)/DT
00112          THCTB = (X3*THETA*THETA+X2)*THETA+X1
00113          IF (T.GE.500.0.AND.T.LE.1800.0) RETURN
00115          WRITE (6,1) T
00120        1 FORMAT (1H0,56HTHERMAL CONDUCTIVITY OF COPPER, TEMP. OUT OF RANGE,
00120         1 T = ,F8.3,/)
00121          RETURN
00122          END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  TK  ******
```

```
@FOR,S ME*NASA5.TK,ME*NASA5.TK
FOR S9A-07/13/72-20:58:46 (0,)

   FUNCTION TK          ENTRY POINT 000211

   STORAGE USED: CODE(1) 000245; DATA(0) 000062; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   ELAS
    0004   ALOG
    0005   NEXP6$
    0006   SQRT
    0007   NWDU$
    0010   NI02$
    0011   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000112 13L       0001     000127 14L       0001     000174 15L       0000     000020 16F       0001     000201 17L
    0000 R 000003 B           0000 R 000001 C           0000 R 000017 CC          0000 R 000004 D           0000 R 000015 E
    0000 R 000002 EE          0003 R 000000 ELAS        0000 R 000005 F           0000 R 000006 G           0000     000040 INJP$
    0000 I 000012 KG          0000 R 000007 P           0000 R 000010 Q           0000 R 000016 R           0000 R 000011 S
    0000 R 000000 TK          0000 R 000013 TN          0000 R 000014 V


00101            FUNCTION  TK(GAMMA,A,BETA,DENSM,THETA,PHI,AN,ALPHA,VELM,
00101           1        PO,TAU,DENST,W,TNN,AMAN,TIN,ROUT)
00101       C
00101       C  THIS FUNCTION SUBPROGRAM COMPUTES :
00101       C    THE THICKNESS OF THE PROTECTION LAYET TK ,IN INCHES
00101       C
00103            DATA C/1.2407013/
00105            EE = 1./(3.*BETA)
00106            B  = GAMMA*A
00107            D  = 0.0436332*TNN*W
00110            F  = (ALPHA*TAU/(-ALOG(PO)))**EE
00111            G  = (1./DENSM)**.33333
00112            P  = (DENSM/DENST)**PHI
00113            Q  = (VELM/(12.0*SQRT(ELAS(TIN)*32.174/DENST)))**THETA
00114            S  = (2./(3.*AN*THETA*BETA+2.))**EE
00115            KG = 0
00116            TN = 0.5
00117         13 KG = KG+1
00120            IF (KG.EQ.1) GO TO 14
00122            IF (KG.GT.10) GO TO 15
00124            TN = TK
00125         14 V  = (D*(ROUT+TN)+AMAN)
00126            E  = V**EE
00127            R  = B*C*E*F*G*P*Q*S
00130            TK = TN-((TN-R)/(1.-(EE*R*D/V)))
```

```
00131     26*           CC = TK/TN-1.
00132     27*           IF (ABS(CC).LT..0001) GO TO 17
00134     28*           GO TO 13
00135     29*        15 WRITE (6,16)
00137     30*        16 FORMAT (29HEQN FOR THICK DOESNT CONVERGE)
00140     31*        17 RETURN
00141     32*           END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  TNH  ******
```

```
@FOR,S ME*NASA5.TNH,ME*NASA5.TNH
FOR S9A-07/13/72-20:58:48 (0,)

   FUNCTION TNH          ENTRY POINT 000056

   STORAGE USED: CODE(1) 000064; DATA(0) 000030; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   CPAIR
    0004   ENTAIR
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000037 10L       0001     000004 106G      0001     000041 30L       0003 R 000000 CPAIR      0000 R 000014 DFTN
    0004 R 000000 ENTAIR    0000 R 000015 FTN       0000     000020 INJP$     0000 I 000013 N          0000 R 000001 TN
    0000 R 000000 TNH


 00101      1*               FUNCTION TNH(ENT)
 00101      2*       C
 00101      3*       C          THIS FUNCTION SUBPROGRAM COMPUTES :
 00101      4*       C          TEMPERATURE OF THE ATMOSPHERE AS A FUNCTION OF ENTHALPY (BTU/LBM)
 00101      5*       C                                               UNITS R
 00101      6*       C
 00103      7*               DIMENSION TN(10)
 00104      8*               TN(1)    = 2500.0
 00105      9*               DO 10 N = 1,10
 00110     10*               DFTN     =  CPAIR(TN(N))
 00111     11*               FTN      =  ENTAIR(TN(N))-ENT
 00112     12*               TN(N+1) =  TN(N)-FTN/DFTN
 00113     13*               IF (N .EQ. 1)  GO TO 10
 00115     14*               IF (ABS(TN(N+1)-TN(N)) .LE. 2.0)  GO TO 30
 00117     15*            10 CONTINUE
 00121     16*            30 TNH      =  TN(N+1)
 00122     17*               RETURN
 00123     18*               END

        END OF COMPILATION:        NO  DIAGNOSTICS.


 @HDG,P  ******  TRMATX  ******
```

```
@FOR,S ME*NASA5.TRMATX,ME*NASA5.TRMATX
FOR S9A-07/13/72-20:58:50 (0,)

   SUBROUTINE TRMATX    ENTRY POINT 000262

   STORAGE USED: CODE(1) 000275; DATA(0) 000051; BLANK COMMON(2) 000000

    COMMON BLOCKS:

    0003   QRD    003721
    0004   ABSRST 000601

   EXTERNAL REFERENCES (BLOCK, NAME)

    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000003 106G     0001   000004 111G     0001   000021 120G     0001   000022 123G     0001   000053 134G
    0001   000056 137G     0001   000066 142G     0001   000121 153G     0001   000137 162G     0001   000145 166G
    0001   000154 171G     0001   000211 201G     0001   000212 204G     0001   000217 211G     0001   000224 216G
    0004 R 000000 ALPHFN   0004 R 000226 ALPHMP   0003 R 003465 CSF      0000 R 000005 CSFXZ    0003 R 003464 DXX2
    0003   003472 DXX21    0003   003463 DZMFN    0003   003410 EBFN     0003   003441 EBMP     0004   000461 EMITFN
    0004   000512 EMITMP   0003   003467 EXTIFN   0003   003471 EXTIMP   0003   003466 EXTSFN   0003   003470 EXTSMP
    0004   000517 EXTVCT   0000 I 000000 I        0000   000027 INJP$    0000 I 000001 J        0000 I 000007 JK
    0000 I 000002 K        0000 I 000004 L        0003   003461 LCT      0003   003462 LTT      0003   003460 MCVRD
    0000 I 000003 M1       0000 I 000006 M2       0003 R 003473 SS       0003 R 003670 SSTT     0003 R 000000 TRMTX
    0003   003446 XX2      0003   003453 ZZ2


00101             SUBROUTINE TRMATX
00101       C
00101       C  THIS SUBROUTINE COMPUTES :
00101       C     THE TRANSFER MATRIX NECESSARY FOR THE CALCULATION OF THE INCIDENT
00101       C     NET RADIANT FLUX
00101       C
00103             COMMON /QRD/ TRMTX(30,60),EBFN(5,5),EBMP(5),XX2(5),ZZ2(5),
00103            1              MCVRD,LCT,LTT,DZMFN,
00103            2              DXX2,CSF,EXTSFN,EXTIFN,EXTSMP,EXTIMP,DXX21,SS(5,5,5)
00103            3              ,SSTT(5,5)
00104             COMMON /ABSRST/ALPHFN(5,5,6),ALPHMP(5,31),EMITFN(5,5),EMITMP(5),
00104            1                 EXTVCT(50)
00105             DO 2 I=1,25
00110             DO 1 J=1,25
00113           1 TRMTX(I,J)=0.0
00115           2 TRMTX(I,I)=1.0
00117             DO 4 I=26,30
00122             DO 3 J=26,30
00125           3 TRMTX(I,J)=-(1.0-ALPHMP(I-25,J))*SSTT(I-25,J-25)*0.25
00127             TRMTX(I,26)=TRMTX(I,26)/2.0
00130             TRMTX(I,30)=TRMTX(I,30)/2.0
```

```
00131         4 TRMTX(I,I)=1.0+TRMTX(I,I)
00133           DO 5 I=1,5
00136           DO 5 J=1,5
00141           DO 5 K=1,5
00144           M1     =25+K
00145           L      =(I-1)*5 +J
00146         5 TRMTX(L,M1) =-(1.0-ALPHFN(I,J,K))*SS(I,J,K)/4.0
00152           DO 6 I=1,25
00155           TRMTX(I,26) =TRMTX(I,26)/2.0
00156         6 TRMTX(I,30) =TRMTX(I,30)/2.0
00160           CSFXZ  = CSF*DXX2/4.0
00161           DO 7  I=1,5
00164           M2      =25+I
00165           DO 7  J=1,5
00170           DO 7  K=1,5
00173           JK      =(J-1)*5+K
00174         7 TRMTX(M2,JK)=-(1.0-ALPHMP(I,JK))*SS(J,K,I)*CSFXZ
00200           DO 10 I=26,30
00203           DO 8  K=21,25
00206         8 TRMTX(I,K)  =TRMTX(I,K)/2.0
00210           DO 9  J=1,21,5
00213         9 TRMTX(I,J)  =TRMTX(I,J)/2.0
00215           DO 10 J=5,25,5
00220        10 TRMTX(I,J)  =TRMTX(I,J)/2.0
00223           RETURN
00224           END

      END OF COMPILATION:       NO  DIAGNOSTICS.
```

@HDG,P ****** TRNSPT ******

```
****** TRNSPT ******                                                      DATE 071372     PAGE    1

@FOR,S ME*NASA5.TRNSPT,ME*NASA5.TRNSPT
FOR S9A-07/13/72-20:58:53 (0,)

   SUBROUTINE TRNSPT    ENTRY POINT 000143

   STORAGE USED: CODE(1) 000171; DATA(0) 000040; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NEXP6$
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000062 10L      0001   000106 15L      0001   000050 5L      0000   000030 INJP$    0000 R 000000 NUL
    0000 R 000001 XX


00101         SUBROUTINE TRNSPT (RE,PRL,DELTA,FR,FNU)                          01
00101    C
00101    C   THIS SUBROUTINE COMPUTES :
00101    C     THE NON-DIMENSIONAL FRICTION FACTOR FR ,AND THE NON-DIMENSIONAL
00101    C     CONVECTIVE FILM COEFFICIENT FNU
00101    C
00103         REAL NUL                                                         02
00103    C                                                                     03
00104         IF (RE.LT.2300.0) GO TO 10                                       04
00106         NUL = 0.116*(RE**0.667-125.0)*PRL**0.3333*(1.0+DELTA**0.667)     05
00107         IF (RE.GT.1.0E+06) GO TO 5                                       06
00111         FR = (0.0054+0.396/RE**0.3)/DELTA                                07
00112         GO TO 15                                                         08
00113       5 FR = (0.0032+0.222/RE**0.237)/DELTA                              09
00114         GO TO 15                                                         010
00115      10 FR = 64.0/(RE*DELTA)                                             011
00116         XX = RE*PRL*DELTA                                                012
00117         NUL = 3.65+0.0668*XX/(1.0+0.045*XX**0.667)
00120      15 IF (PRL.LT.0.1) NUL = 6.5+0.025*(RE*PRL)**0.8                    014
00122         FNU = 4.0*NUL/(DELTA*RE*PRL)                                     015
00123         RETURN                                                           016
00124         END                                                              017

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  TTIP  ******
```

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****** TTIP ******                                                                DATE 071372      PAGE    1

@FOR,S ME*NASA5.TTIP,ME*NASA5.TTIP
FOR S9A-07/13/72-20:58:55 (0,)

   SUBROUTINE TTIP      ENTRY POINT 000043

   STORAGE USED: CODE(1) 000060; DATA(0) 000101; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   POLY
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000005 1166     0001   000007 121G     0000 R 000043 AA      0000 R 000000 CC      0000 R 000052 COEF
    0000 I 000057 I        0000   000067 INJP$    0000 I 000060 J       0003 R 000000 POLY


00101            SUBROUTINE TTIP (NC,TSOTB,TLOTB)
00103            DIMENSION CC(5,7),AA(7),COEF(5)
00104            REAL NC
00105            DATA(CC(I,2),I=1,5)/-.4815,-.8920814,4.894438,-14.89583,10.39930/,
00105           1 (CC(I,3),I=1,5)/.5365006,.7351966,-12.35190,40.88471,-30.65782/,
00105           2 (CC(I,4),I=1,5)/-.440667,.2304286,11.64157,-44.56229,35.26028/,
00105           3 (CC(I,5),I=1,5)/.212667,-.4978796,-5.648548,24.37024,-19.93047/,
00105           4 (CC(I,6),I=1,5)/-.05333347,.198336,1.40554,-6.58330,5.48609/,
00105           5 (CC(I,7),I=1,5)/.00533335,-.02525962,-.139998,.6925878,-.5833303/
00114            AA(1)    =  1.0
00115            DO 20  I=2,7
00120            DO 10  J=1,5
00123         10 COEF(J) =  CC(J,I)
00125         20 AA(I)    =  POLY (5,COEF,TSOTB)
00127            TLOTB    =  POLY (7,AA,NC)
00130            RETURN
00131            END

      END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  TTIPS  ******
```

```
@FOR,S ME*NASA5.TTIPS,ME*NASA5.TTIPS
FOR S9A-07/13/72-20:58:57 (0,)

  SUBROUTINE TTIPS     ENTRY POINT 000345

  STORAGE USED: CODE(1) 000366; DATA(0) 000110; BLANK COMMON(2) 000000

   COMMON BLOCKS:

   0003   ADBH    000352
   0004   QIN     001610

  EXTERNAL REFERENCES (BLOCK, NAME)

   0005    NUSA
   0006    EFFICY
   0007    TTIP
   0010    EXP
   0011    NEXP6$
   0012    NPRT$
   0013    NIO2$
   0014    NSTOP$
   0015    NERR3$

  STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

   0000   000041 105F      0001   000303 110L      0001   000136 136G      0001   000120 20L       0001   000126 30L
   0000 R 000033 AA        0003 R 000001 AL        0000 R 000021 BB1       0000 R 000022 BB2       0000 R 000006 COEF
   0003 R 000161 CONFL     0003 R 000173 CONFNA    0003 R 000147 CP        0000 R 000013 C1        0000 R 000014 C2
   0000 R 000030 C4        0000 R 000020 C5        0003 R 000000 D         0000 R 000035 OFNTB     0000 R 000011 DOL
   0000 R 000036 DTB       0003   000326 DTL       0003 R 000244 EFF       0003 R 000205 EMIS      0000 R 000025 ETAPRI
   0000 R 000027 ETAPR2    0000 R 000024 ETA1      0000 R 000026 ETA2      0000 R 000034 FNTB      0003   000013 H
   0003   000231 HAB       0000   000064 INJP$     0000 I 000017 L         0003 R 000064 M         0000 R 000002 NCPR1
   0000 R 000003 NCPR2     0000 R 000000 NC1       0000 R 000001 NC2       0004 I 001605 NSRD      0003   000076 NT
   0004   001604 NTM       0005 R 000000 NUSA      0000 R 000004 PI        0003   000052 PIN       0000 R 000007 PR
   0004   000454 QIFN      0004   001274 QITB      0003   000314 QOUT      0004   000144 QSFN      0004   000764 QSTB
   0004   001606 QTO       0000 R 000010 REY       0000 R 000005 SIGMA     0003 R 000217 TB        0000 R 000031 TB3
   0000 R 000032 TB4       0003 R 000026 TH        0003 R 000040 TIN       0003   000270 TL        0000 R 000037 TLOTB1
   0000 R 000040 TLOTB2    0004   000000 TM        0003   000340 TOUT      0000 R 000023 TSOTB     0003 R 000077 TSTAR
   0000 R 000016 TSTR      0000 R 000015 TS4       0004   001607 TX        0000 R 000012 U         0003 R 000135 VSC


 00101      1*                SUBROUTINE TTIPS(IT,ITST,H1,H2,TL1,TL2)
 00103      2*                PARAMETER NTP = 10
 00104      3*                PARAMETER NTP1 = NTP+1
 00105      4*                REAL M
 00106      5*                COMMON /AOBH/ D,AL(NTP),H(NTP1),TH(NTP),TIN(NTP),PIN(NTP),
 00106      6*             1  M(NTP),NT,TSTAR(NTP,3),VSC(NTP),CP(NTP),CONFL(NTP),
 00106      7*             2  CONFNA(NTP),EMIS(NTP),TB(NTP),HAB(NTP1),EFF(NTP,2),TL(NTP,2),
 00106      8*             3  QOUT(NTP),DTL(NTP),TOUT(NTP)
 00107      9*                COMMON /QIN/ TM(100),QSFN(100,2),QIFN(100,2),QSTB(100,2),
```

```
00107            1    QITB(100,2),NTM,NSRD,QTO,TX
00110                REAL NUSA,NC1,NC2,NCPR1,NCPR2
00111                DATA PI/3.1415927/
00113                DATA SIGMA/1.714E-9/
00115                COEF=EMIS(IT)*SIGMA/(CONFNA(IT)*TM(IT))
00116                PR=VSC(IT)*CP(IT)/CONFL(IT)
00117                REY=48*M(IT)/(PI*D*VSC(IT))
00120                DOL=D/(12*AL(IT))
00121                U=PI*CONFL(IT)*AL(IT)*NUSA(REY,PR,DOL)/(M(IT)*CP(IT))
00122                C1=M(IT)*CP(IT)*(1-EXP(-U))
00123                C2=NSRD*EMIS(IT)*SIGMA*AL(IT)/12
00124                TB(IT)=.9*TIN(IT)
00125                IF(NSRD.NE.2)GO TO 20
00127                TS4=(TSTAR(IT,1)**4+TSTAR(IT,2)**4)/2
00130                TSTR=TS4**.25
00131                GO TO 30
00132        20      TS4=TSTAR(IT,ITST)**4
00133                TSTR=TSTAR(IT,ITST)
00134        30      CONTINUE
00135                DO 100 L=2,10
00140                C5=TB(IT)**2*COEF/12
00141                BB1=C5*H1**2
00142                BB2=C5*H2**2
00143                NC1=TB(IT)*BB1
00144                NC2=TB(IT)*BB2
00145                NCPR1=3*BB1
00146                NCPR2=3*BB2
00147                TSOTB=TSTR/TB(IT)
00150                CALL EFFICY(NC1,NCPR1,TSOTB,TB(IT),ETA1,ETAPR1)
00151                    EFF(IT,1) = ETA1*100.0
00152                CALL EFFICY(NC2,NCPR2,TSOTB,TB(IT),ETA2,ETAPR2)
00153                    EFF(IT,2) = ETA2*100.0
00154                C4=ETA1*H1+ETA2*H2
00155                TB3=TB(IT)**3
00156                TB4=TB3*TB(IT)
00157                AA=TB4-TS4
00160                FNTB=C1*(TIN(IT)-TB(IT))-C2*C4*AA
00161                DFNTB=-C1-C2*(4*TB3*C4+AA*(ETAPR1*H1+ETAPR2*H2))
00162                DTB=FNTB/DFNTB
00163                TB(IT)=TB(IT)-DTB
00164                IF(ABS(DTB).LE.0.005)GO TO 110
00166       100      CONTINUE
00170                    PRINT 105
00172       105      FORMAT(' BASE TEMPERATURE DOES NOT CONVERGE')
00173                STOP
00174       110      CONTINUE
00175                CALL TTIP(NC1,TSOTB,TLOTB1)
00176                CALL TTIP(NC2,TSOTB,TLOTB2)
00177                TL1=TLOTB1*(TB(IT)-TSTR)+TSTR
00200                TL2=TLOTB2*(TB(IT)-TSTR)+TSTR
00201                RETURN
00202                END

      END OF COMPILATION:       NO  DIAGNOSTICS.
```

QHDG,P ****** VISC/CFFC43 ******

```
@FOR,S ME*NASA5.VISC/CFFC43,ME*NASA5.VISC/CFFC43
FOR S9A-07/13/72-20:59:00 (0,)

   FUNCTION VISC        ENTRY POINT 000032

   STORAGE USED: CODE(1) 000036; DATA(0) 000021; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   EXP
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000006 DT        0000   000012 INJP$     0000 R 000007 THETA     0000 R 000005 TO        0000 R 000000 VISC
    0000 R 000010 VNU       0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3        0000 R 000004 X4


00101      1*           FUNCTION VISC(RHO,T)
00101      2*      C
00101      3*      C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*      C       VISCOSITY AS A FUNCTION OF DENSITY (SLUG/CU.FT)
00101      5*      C            AND TEMPERATURE (R) OF FC-43
00101      6*      C                                     UNITS SLUG/(FT.HR)
00101      7*      C
00103      8*           DATA X1,X2,X3,X4 /2.76,-2.043483,0.362,-0.034717/,TO,DT /439.67,90
00103      9*          1.0/
00112     10*           THETA = (T-TO)/DT
00113     11*           VNU   = EXP(((X4*THETA+X3)*THETA+X2)*THETA+X1)
00114     12*           VISC = VNU*RHO*0.03875
00115     13*           RETURN
00116     14*           END

      END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  VISC/CFFC75  ******
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```
@FOR,S ME*NASA5.VISC/CFFC75,ME*NASA5.VISC/CFFC75
FOR S9A-07/13/72-20:59:03 (0,)

   FUNCTION VISC          ENTRY POINT 000032

   STORAGE USED: CODE(1) 000036; DATA(0) 000021; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   EXP
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000006 DT       0000   000012 INJP$     0000 R 000007 THETA     0000 R 000005 TO        0000 R 000000 VISC
    0000 R 000010 VNU      0000 R 000001 X1        0000 R 000002 X2        0000 R 000003 X3        0000 R 000004 X4


00101              FUNCTION VISC(RHO,T)
00101        C
00101        C        THIS FUNCTION SUBPROGRAM COMPUTES :
00101        C        VISCOSITY AS A FUNCTION OF DENSITY (SLUG/CU.FT)
00101        C             AND TEMPERATURE (R) OF FC-75
00101        C                                     UNITS SLUG/(FT.HR)
00101        C
00103              DATA X1,X2,X3,X4 /1.639,-1.312933,0.25265,-0.02471667/,TO,DT / 409
00103             1.67,60.0/
00112              THETA = (T-TO)/DT
00113              VNU   = EXP(((X4*THETA+X3)*THETA+X2)*THETA+X1)
00114              VISC = VNU*RHO*0.03875
00115              RETURN
00116              END

       END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  VISC/CFHE  ******
```

```
@FOR,S ME*NASA5.VISC/CFHE,ME*NASA5.VISC/CFHE
FOR S9A-07/13/72-20:59:04 (0,)

    FUNCTION VISC         ENTRY POINT 000016

    STORAGE USED: CODE(1) 000022; DATA(0) 000011; BLANK COMMON(2) 000000

    EXTERNAL REFERENCES (BLOCK, NAME)

     0003   NEXP6$
     0004   NERR3$

    STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

     0000   000003 INJP$     0000 R 000000 VISC


 00101      1*             FUNCTION VISC(RHO,T)
 00101      2*       C
 00101      3*       C         THIS FUNCTION SUBPROGRAM COMPUTES :
 00101      4*       C         VISCOSITY AS A FUNCTION OF DENSITY (SLUG/CU.FT)
 00101      5*       C              AND TEMPERATURE (R) OF HELIUM
 00101      6*       C                                      UNITS SLUG/(FT.HR)
 00101      7*       C
 00103      8*             VISC = 2.58394E-05*T**0.647
 00104      9*             RETURN
 00105     10*             END
       END OF COMPILATION:        NO  DIAGNOSTICS.


 @HDG,P  ******  VISC/CFNAK  ******
```

```
@FOR,S ME*NASA5.VISC/CFNAK,ME*NASA5.VISC/CFNAK
FOR S9A-07/13/72-20:59:07 (0,)

   FUNCTION VISC        ENTRY POINT 000025

   STORAGE USED: CODE(1) 000027; DATA(0) 000017; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000 R 000007 DT         0000   000012 INJP$     0000 R 000010 THETA     0000 R 000006 TO        0000 R 000000 VISC
    0000 R 000001 X1         0000 R 000002 X2        0000 R 000003 X3        0000 R 000004 X4        0000 R 000005 X5


00101      1*          FUNCTION VISC(RHO,T)
00101      2*     C
00101      3*     C       THIS FUNCTION SUBPROGRAM COMPUTES :
00101      4*     C       VISCOSITY AS A FUNCTION OF DENSITY (SLUG/CU.FT)
00101      5*     C            AND TEMPERATURE (R) OF NAK 78.6
00101      6*     C                                    UNITS SLUG/(FT.HR)
00101      7*     C
00103      8*          DATA X1,X2,X3,X4,X5 /1.316,-0.896667,0.419833,-0.102833,0.009667/,
00103      9*         1TO,DT /659.67,300.0/
00113     10*          THETA = (T-TO)/DT
00114     11*          VISC  = ((((X5*THETA+X4)*THETA+X3)*THETA+X2)*THETA+X1)/32.174
00115     12*          RETURN
00116     13*          END

      END OF COMPILATION:       NO  DIAGNOSTICS.


@HDG,P  ******  VISC/CFSIL  ******
```

```
@FOR,S ME*NASA5.VISC/CFSIL,ME*NASA5.VISC/CFSIL
FOR S9A-07/13/72-20:59:09 (0,)

   FUNCTION VISC        ENTRY POINT 000061

   STORAGE USED: CODE(1) 000067; DATA(0) 000040; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   EXP
    0004   NWDU$
    0005   NI02$
    0006   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000     000011 1F        0000 R 000006 DT        0000   000030 INJP$      0000 R 000007 THETA      0000 R 000005 TO
    0000 R 000000 VISC        0000 R 000010 VNU       0000 R 000001 X1         0000 R 000002 X2         0000 R 000003 X3
    0000 R 000004 X4


C
C        THIS FUNCTION SUBPROGRAM COMPUTES :
      FUNCTION VISC(RHO,T)
C        VISCOSITY AS A FUNCTION OF DENSITY (SLUG/CU.FT) AND
C             TEMPERATURE (R) OF DOW CORNING 200 SILICON OIL (1 CS)
C                                     UNITS SLUG/(FT.HR)
C             TEMPERATURE .GE. 359.67 AND .LE. 859.67
C
      DATA X1,X2,X3,X4 /0.683,-1.0845,0.3065,-0.04/,TO,DT /459.67,100.0/
      THETA = (T-TO)/DT
      VNU   = EXP(((X4*THETA+X3)*THETA+X2)*THETA+X1)
      VISC = VNU*RHO*0.03875
      IF (T.GE.360.67.AND.T.LE.860.67) RETURN
      WRITE (6,1) T
    1 FORMAT (1H0,50HVISCOSITY OF SILICON OIL, TEMP. OUT OF RANGE, T = ,
     1F8.3,/)
      RETURN
      END

        END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  YINT  ******
```

```
@FOR,S ME*NASA5.YINT,ME*NASA5.YINT
FOR S9A-07/13/72-20:59:11 (0,)

   FUNCTION YINT        ENTRY POINT 000265

   STORAGE USED: CODE(1) 000315; DATA(0) 000136; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NWDU$
    0004   NIO2$
    0005   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001    000075 113G      0001    000146 130G      0001    000172 140G      0001    000201 143G      0001    000215 150G
    0001    000106 2L        0001    000230 6L        0000    000060 7F        0001    000240 8L        0000    000072 9F
    0000 I  000053 I         0000    000111 INJP$     0000 I  000057 J         0000 I  000056 L         0000 I  000055 ME
    0000 I  000051 MM        0000 I  000054 M0        0000 I  000052 M1        0000 R  000013 XP        0000 R  000025 XQ
    0000 R  000001 XX        0000 R  000000 YINT      0000 R  000037 YY


 00101            FUNCTION YINT(X,Y,N,M,P)
 00101        C
 00101        C  THIS SUBROUTINE COMPUTES :
 00101        C     AITKEN INTERPOLATION
 00101        C     X ARRAY OF ABSCISSAE
 00101        C     Y ARRAY OF ORDINATES
 00101        C     N NUMBER OF ELEMENTS IN ARRAYS X AND Y
 00101        C     P X-VALUE OF INTERPOLATION
 00101        C     M DEGREE OF POLYNOMIAL PASSING THROUGH Y(X) IN THE VICINITY OF P
 00101        C
 00103            DIMENSION X(N),Y(N),XX(10),XP(10),XQ(10),YY(10)
 00104            IF(P.LT.(2.*X(1)-X(2)).OR.P.GT.(2.*X(N)-X(N-1))) GO TO 8
 00106                MM = MAX(MIN(M,10),2)
 00107                 IF (N.LT.MM.OR.N.LE.2) GO TO 6
 00111                M1 = MM/2
 00112            DO 1 I = 1,N
 00115            IF (P .LE. X(I)) GO TO 2
 00117          1 CONTINUE
 00121          2 M0     =  I-M1
 00122            ME     = M0+MM-1
 00123            IF (M0 .LT. 1) M0 = 1
 00125            IF (ME .GT. N) M0 = N-MM+1
 00127            DO 3 I = 1,MM
 00132            L      =  M0+I-1
 00133            XP(I)  =  X(L)-P
 00134            XQ(I)  =  X(L)
 00135          3 YY(I)  =  Y(L)
 00137            DO 5 I = 2,MM
 00142            DO 4 J = I,MM
```

```
00145          4  XX(J) =  (YY(I-1)*XP(J)-YY(J)*XP(I-1))/(XQ(J)-XQ(I-1))
00147             DO 5 J = 1,MM
00152          5  YY(J) =  XX(J)
00155             YINT   =  YY(MM)
00156             RETURN
00157          6 WRITE (6,7)
00161          7 FORMAT (/,1X,45HINTERPOL. IS IMPOSSIBLE, DATA ARRAY TOO SMALL)
00162             RETURN
00163          8 WRITE (6,9) P
00166          9 FORMAT (/,1X,29HINTERPOL. IS IMPOSSIBLE, P = ,E12.4,12HOUT OF RANG
00166           1E)
00167             RETURN
00170             END

       END OF COMPILATION:        NO  DIAGNOSTICS.


@HDG,P  ******  CFFC43  ******
```

```
@ELT,L ME*NASA5.CFFC43
ELT 005-07/13-20:59
000001      000   CLASS     CFFC43
000002      000   IN        BETA,CAPPA,CPF,HFL,RHOF,THCF,VISC
000003      000   DEF       BETA,CAPPA,CPF,HFL,RHOF,THCF,VISC
000004      000   END
```

```
@HDG,P  ******  CFFC75  ******
```

```
@ELT,L ME*NASA5.CFFC75
ELT 005-07/13-20:59
000001      000   CLASS     CFFC75
000002      000   IN        BETA,CAPPA,CPF,HFL,RHOF,THCF,VISC
000003      000   DEF       BETA,CAPPA,CPF,HFL,RHOF,THCF,VISC
000004      000   END


@HDG,P  ******  CFHE  ******
```

```
@ELT,L ME*NASA5.CFHE
ELT 005-07/13-20:59
000001      000   CLASS      CFHE
000002      000   IN         BETA,CAPPA,CPF,HFL,PF,RHOF,THCF,VISC
000003      000   DEF        BETA,CAPPA,CPF,HFL,PF,RHOF,THCF,VISC
000004      000   END
```

```
@HDG,P  ******  CFNAK  ******
```

```
@ELT,L ME*NASA5.CFNAK
ELT 005-07/13-20:59
000001      000   CLASS     CFNAK
000002      000   IN        BETA,CAPPA,CPF,HFL,PF,RHOF,THCF,VISC
000003      000   DEF       BETA,CAPPA,CPF,HFL,PF,RHOF,THCF,VISC
000004      000   END

@HDG,P  ******  CFSIL  ******
```

```
@ELT,L ME*NASA5.CFSIL
ELT 005-07/13-20:59
000001      000   CLASS    CFSIL
000002      000   IN       BETA,CAPPA,CPF,HFL,PF,RHOF,THCF,VISC
000003      000   DEF      BETA,CAPPA,CPF,HFL,PF,RHOF,THCF,VISC
000004      000   END


@HDG,P  ******  FNAL  ******
```

```
@ELT,L ME*NASA5.FNAL
ELT 005-07/13-20:59
000001      000   CLASS     FNAL
000002      000   IN        CPFN,DTHCFN,THCFN
000003      000   DEF       CPFN,DTHCFN,THCFN
000004      000   END
```

@HDG,P ****** FNBR ******

```
****** FNBR ******                                                    DATE 071372      PAGE    1

@ELT,L ME*NASA5.FNBR
ELT 005-07/13-20:59
000001      000   CLASS      FNBR
000002      000   IN         CPFN,DTHCFN,THCFN
000003      000   DEF        CPFN,DTHCFN,THCFN
000004      000   END

@HDG,P   ******  FNCU  ******
```

```
@ELT,L ME*NASA5.FNCU
ELT 005-07/13-20:59
000001       000   CLASS     FNCU
000002       000   IN        CPFN,DTHCFN,THCFN
000003       000   DEF       CPFN,DTHCFN,THCFN
000004       000   END

@HDG,P  ******  MPAL  ******
```

```
@ELT,L ME*NASA5.MPAL
ELT 005-07/13-20:59
000001       000   CLASS      MPAL
000002       000   IN         CPMP,DTHCMP,ELAS,THCMP
000003       000   DEF        CPMP,DTHCMP,ELAS,THCMP
000004       000   END
```

```
@HDG,P  ******  MPBR  ******
```

```
@ELT,L ME*NASA5.MPBR
ELT 005-07/13-20:59
000001     000  CLASS    MPBR
000002     000  IN       CPMP,DTHCMP,ELAS,THCMP
000003     000  DEF      CPMP,DTHCMP,ELAS,THCMP
000004     000  END
```

@HDG,P ****** MPCU ******

```
******  MPCU  ******                                                                   DATE 071372       PAGE    1

@ELT,L ME*NASA5.MPCU
ELT 005-07/13-20:59
000001       000   CLASS      MPCU
000002       000   IN         CPMP,DTHCMP,ELAS,THCMP
000003       000   DEF        CPMP,DTHCMP,ELAS,THCMP
000004       000   END


@HDG,P  ******  SC293  ******
```

```
****** SCZ93 ******                                                      DATE 071372        PAGE     1

@ELT,L ME*NASA5.SCZ93
ELT 005-07/13-20:59
000001      000   CLASS     SCZ93
000002      000   IN        AVGEMT,EMIT
000003      000   DEF       AVGEMT,EMIT
000004      000   END


@HDG,P  ******  TBAL  ******
```

```
****** TBAL ******                                                              DATE 071372        PAGE     1

@ELT,L ME*NASA5.TBAL
ELT 005-07/13-20:59
000001       000   CLASS      TBAL
000002       000   IN         CPTB,DTHCTB,THCTB
000003       000   DEF        CPTB,DTHCTB,THCTB
000004       000   END


@HDG,P  ******  TBBR  ******
```

```
@ELT,L ME*NASA5.TBBR
ELT 005-07/13-20:59
000001        000   CLASS     TBBR
000002        000   IN        CPTB,DTHCTB,THCTB
000003        000   DEF       CPTB,DTHCTB,THCTB
000004        000   END


@HDG,P  ******  TBCU  ******
```

```
@ELT,L ME*NASA5.TBCU
ELT 005-07/13-20:59
000001       000   CLASS     TBCU
000002       000   IN        CPTB,DTHCTB,THCTB
000003       000   DEF       CPTB,DTHCTB,THCTB
000004       000   END


@HDG,P  ******  VER1  ******
```

```
****** VER1 ******                                                DATE 071372        PAGE     1

@ELT,L ME*NASAS.VER1
ELT 005-07/13-20:59
000001      000   IN       CFSIL,FNAL,MPBR,TBAL,SCZ93
000002      000   IN       MAIN
000003      000   END


@HDG,N


@HDG,P  ******  CFFC43  ******
```

```
****** CFFC43 ******                                                        DATE 071372        PAGE     1

@MAP,RS   ME*NASA5.CFFC43
MAP 0023-07/13-20:59 -(0,)

    1.NEW   LIB        ME*NASA5.

    2.      CLASS      CFFC43

    3.      IN         BETA,CAPPA,CPF,HFL,RHOF,THCF,VISC

    4.      DEF        BETA,CAPPA,CPF,HFL,RHOF,THCF,VISC

    5.      END



      R-OPTION COLLECTION


LENGTHS OF LOCATION COUNTERS ASSIGNED
$(1)  COMBINED ODD COUNTERS      000164  OCTAL        116  DECIMAL
$(2)  COMBINED EVEN COUNTERS     000105  OCTAL         69  DECIMAL
  3   COMMONBLOCK BLANK$COMMON   000000  OCTAL          0  DECIMAL



      COMBINED ELEMENTS

BETA/CFFC43             1    000000 000016      0    000000 000007
                                                2    BLANK$COMMON
CAPPA/CFFC43            1    000017 000030      0    000010 000015
                                                2    BLANK$COMMON
CPF/CFFC43              1    000031 000046      0    000016 000026
                                                2    BLANK$COMMON
HFL/CFFC43              1    000047 000072      0    000027 000042
                                                2    BLANK$COMMON
RHOF/CFFC43             1    000073 000110      0    000043 000053
                                                2    BLANK$COMMON
THCF/CFFC43             1    000111 000125      0    000054 000063
                                                2    BLANK$COMMON
VISC/CFFC43             1    000126 000163      0    000064 000104
                                                2    BLANK$COMMON

END OF COLLECTION - TIME 0.303 SECONDS
```

QHDG,P ****** CFFC75 ******

```
****** CFFC75 ******                                                    DATE 071372        PAGE    1

@MAP,RS   ME*NASA5.CFFC75
MAP 0023-07/13-20:59 -(0,)

    1.NEW    LIB        ME*NASA5.

    2.       CLASS      CFFC75

    3.       IN         BETA,CAPPA,CPF,HFL,RHOF,THCF,VISC

    4.       DEF        BETA,CAPPA,CPF,HFL,RHOF,THCF,VISC

    5.       END



      R-OPTION COLLECTION


LENGTHS OF LOCATION COUNTERS ASSIGNED
$(1)  COMBINED ODD COUNTERS     000164  OCTAL       116  DECIMAL
$(2)  COMBINED EVEN COUNTERS    000105  OCTAL        69  DECIMAL
  3   COMMONBLOCK BLANK$COMMON 000000  OCTAL         0  DECIMAL



      COMBINED ELEMENTS

BETA/CFFC75              1    000000 000016      0   000000 000007
                                                 2   BLANK$COMMON
CAPPA/CFFC75             1    000017 000030      0   000010 000015
                                                 2   BLANK$COMMON
CPF/CFFC75               1    000031 000046      0   000016 000026
                                                 2   BLANK$COMMON
HFL/CFFC75               1    000047 000072      0   000027 000042
                                                 2   BLANK$COMMON
RHOF/CFFC75              1    000073 000110      0   000043 000053
                                                 2   BLANK$COMMON
THCF/CFFC75              1    000111 000125      0   000054 000063
                                                 2   BLANK$COMMON
VISC/CFFC75              1    000126 000163      0   000064 000104
                                                 2   BLANK$COMMON

END OF COLLECTION - TIME 0.203 SECONDS
```

****** CFHE ****** DATE 071372 PAGE 1

```
@MAP,RS   ME*NASA5.CFHE
MAP 0023-07/13-20:59 -(0,)

   1.NEW    LIB       ME*NASA5.

   2.       CLASS     CFHE

   3.       IN        BETA,CAPPA,CPF,HFL,PF,RHOF,THCF,VISC

   4.       DEF       BETA,CAPPA,CPF,HFL,PF,RHOF,THCF,VISC

   5.       END
```

R-OPTION COLLECTION

```
LENGTHS OF LOCATION COUNTERS ASSIGNED
$(1)  COMBINED ODD COUNTERS     000635  OCTAL       413  DECIMAL
$(2)  COMBINED EVEN COUNTERS    000267  OCTAL       183  DECIMAL
  3   COMMONBLOCK BLANK$COMMON 000000  OCTAL         0  DECIMAL
```

COMBINED ELEMENTS

```
BETA/CFHE            1   000000 000111     0   000000 000036
                                           2   BLANK$COMMON
CAPPA/CFHE           1   000112 000200     0   000037 000067
                                           2   BLANK$COMMON
CPF/CFHE             1   000201 000271     0   000070 000120
                                           2   BLANK$COMMON
HFL/CFHE             1   000272 000415     0   000121 000167
                                           2   BLANK$COMMON
PF/CFHE              1   000416 000467     0   000170 000215
                                           2   BLANK$COMMON
RHOF/CFHE            1   000470 000566     0   000216 000240
                                           2   BLANK$COMMON
THCF/CFHE            1   000567 000612     0   000241 000255
                                           2   BLANK$COMMON
VISC/CFHE            1   000613 000634     0   000256 000266
                                           2   BLANK$COMMON
```

END OF COLLECTION - TIME 0.315 SECONDS

****** CFHE ****** DATE 071372 PAGE 2

ΘHDG,P ****** CFNAK ******

```
******   CFNAK   ******                                                                   DATE 071372        PAGE     1

@MAP,RS   ME*NASAS.CFNAK
MAP 0023-07/13-20:59 -(0,)

    1.NEW   LIB       ME*NASAS.

    2.      CLASS     CFNAK

    3.      IN        BETA,CAPPA,CPF,HFL,PF,RHOF,THCF,VISC

    4.      DEF       BETA,CAPPA,CPF,HFL,PF,RHOF,THCF,VISC

    5.      END



      R-OPTION COLLECTION


LENGTHS OF LOCATION COUNTERS ASSIGNED
$(1)  COMBINED ODD COUNTERS     000467  OCTAL        311  DECIMAL
$(2)  COMBINED EVEN COUNTERS    000224  OCTAL        148  DECIMAL
  3   COMMONBLOCK BLANK$COMMON  000000  OCTAL          0  DECIMAL



      COMBINED ELEMENTS

BETA/CFNAK                1    000000 000016      0   000000 000007
                                                  2   BLANK$COMMON
CAPPA/CFNAK               1    000017 000073      0   000010 000041
                                                  2   BLANK$COMMON
CPF/CFNAK                 1    000074 000177      0   000042 000073
                                                  2   BLANK$COMMON
HFL/CFNAK                 1    000200 000311      0   000074 000132
                                                  2   BLANK$COMMON
PF/CFNAK                  1    000312 000351      0   000133 000147
                                                  2   BLANK$COMMON
RHOF/CFNAK                1    000352 000411      0   000150 000166
                                                  2   BLANK$COMMON
THCF/CFNAK                1    000412 000437      0   000167 000204
                                                  2   BLANK$COMMON
VISC/CFNAK                1    000440 000466      0   000205 000223
                                                  2   BLANK$COMMON

END OF COLLECTION - TIME 0.273 SECONDS
```

@HDG,P ****** CFSIL ******

```
@MAP,RS   ME*NASA5.CFSIL
MAP 0023-07/13-20:59 -(0,)

     1.NEW   LIB      ME*NASA5.

     2.      CLASS    CFSIL

     3.      IN       BETA,CAPPA,CPF,HFL,PF,RHOF,THCF,VISC

     4.      DEF      BETA,CAPPA,CPF,HFL,PF,RHOF,THCF,VISC

     5.      END




       R-OPTION COLLECTION


LENGTHS OF LOCATION COUNTERS ASSIGNED
$(1)  COMBINED ODD COUNTERS      001734  OCTAL       988  DECIMAL
$(2)  COMBINED EVEN COUNTERS     000717  OCTAL       463  DECIMAL
  3   COMMONBLOCK BLANK$COMMON 000000  OCTAL         0  DECIMAL




       COMBINED ELEMENTS

BETA/CFSIL            1   000000 000176      0   000000 000075
                                             2   BLANK$COMMON
CAPPA/CFSIL           1   000177 000344      0   000076 000161
                                             2   BLANK$COMMON
CPF/CFSIL             1   000345 000736      0   000162 000314
                                             2   BLANK$COMMON
HFL/CFSIL             1   000737 001264      0   000315 000446
                                             2   BLANK$COMMON
PF/CFSIL              1   001265 001446      0   000447 000540
                                             2   BLANK$COMMON
RHOF/CFSIL            1   001447 001575      0   000541 000625
                                             2   BLANK$COMMON
THCF/CFSIL            1   001576 001644      0   000626 000656
                                             2   BLANK$COMMON
VISC/CFSIL            1   001645 001733      0   000657 000716
                                             2   BLANK$COMMON

END OF COLLECTION - TIME 0.469 SECONDS
```

QHDG,P ****** FNAL ******

```
@MAP,RS   ME*NASA5.FNAL
MAP 0023-07/13-20:59 -(0,)

    1.NEW   LIB       ME*NASA5.
    2.      CLASS     FNAL
    3.      IN        CPFN,DTHCFN,THCFN
    4.      DEF       CPFN,DTHCFN,THCFN
    5.      END


      R-OPTION COLLECTION

LENGTHS OF LOCATION COUNTERS ASSIGNED
$(1)  COMBINED ODD COUNTERS      000202  OCTAL       130  DECIMAL
$(2)  COMBINED EVEN COUNTERS     000116  OCTAL        78  DECIMAL
  3   COMMONBLOCK BLANK$COMMON 000000  OCTAL         0  DECIMAL


      COMBINED ELEMENTS

CPFN/FNAL               1    000000 000061      0    000000 000037
                                                2    BLANK$COMMON
DTHCFN/FNAL             1    000062 000121      0    000040 000056
                                                2    BLANK$COMMON
THCFN/FNAL              1    000122 000201      0    000057 000115
                                                2    BLANK$COMMON

END OF COLLECTION - TIME 0.171 SECONDS


@HDG,P  ******  FNBR  ******
```

```
@MAP,RS   ME*NASA5.FNBR
MAP 0023-07/13-20:59 -(0,)

    1.NEW    LIB       ME*NASA5.
    2.       CLASS     FNBR
    3.       IN        CPFN,DTHCFN,THCFN
    4.       DEF       CPFN,DTHCFN,THCFN
    5.       END




      R-OPTION COLLECTION


LENGTHS OF LOCATION COUNTERS ASSIGNED
$(1)  COMBINED ODD COUNTERS       000200  OCTAL      128  DECIMAL
$(2)  COMBINED EVEN COUNTERS      000115  OCTAL       77  DECIMAL
  3   COMMONBLOCK BLANK$COMMON    000000  OCTAL        0  DECIMAL



      COMBINED ELEMENTS

CPFN/FNBR               1   000000 000057      0   000000 000036
                                               2   BLANK$COMMON
DTHCFN/FNBR             1   000060 000117      0   000037 000055
                                               2   BLANK$COMMON
THCFN/FNBR              1   000120 000177      0   000056 000114
                                               2   BLANK$COMMON

END OF COLLECTION - TIME 0.169 SECONDS


@HDG,P  ****** FNCU  ******
```

```
@MAP,RS   ME*NASA5.FNCU
MAP 0023-07/13-20:59 -(0,)

     1.NEW    LIB        ME*NASA5.

     2.       CLASS      FNCU

     3.       IN         CPFN,DTHCFN,THCFN

     4.       DEF        CPFN,DTHCFN,THCFN

     5.       END



       R-OPTION COLLECTION

LENGTHS OF LOCATION COUNTERS ASSIGNED
$(1)  COMBINED ODD COUNTERS     000163  OCTAL       115  DECIMAL
$(2)  COMBINED EVEN COUNTERS    000102  OCTAL        66  DECIMAL
  3   COMMONBLOCK BLANK$COMMON  000000  OCTAL         0  DECIMAL



       COMBINED ELEMENTS

CPFN/FNCU                 1    000000 000050     0    000000 000030
                                                 2    BLANK$COMMON
DTHCFN/FNCU               1    000051 000105     0    000031 000045
                                                 2    BLANK$COMMON
THCFN/FNCU                1    000106 000162     0    000046 000101
                                                 2    BLANK$COMMON

END OF COLLECTION - TIME 0.165 SECONDS


@HDG,P  ******  MPAL  ******
```

```
@MAP,RS   ME*NASA5.MPAL
MAP 0023-07/13-20:59 -(0,)

     1.NEW     LIB        ME*NASA5.
     2.        CLASS      MPAL
     3.        IN         CPMP,DTHCMP,ELAS,THCMP
     4.        DEF        CPMP,DTHCMP,ELAS,THCMP
     5.        END



       R-OPTION COLLECTION

LENGTHS OF LOCATION COUNTERS ASSIGNED
$(1)   COMBINED ODD COUNTERS     000263  OCTAL       179  DECIMAL
$(2)   COMBINED EVEN COUNTERS    000156  OCTAL       110  DECIMAL
  3    COMMONBLOCK BLANK$COMMON 000000  OCTAL         0  DECIMAL



       COMBINED ELEMENTS

CPMP/MPAL                 1   000000 000061      0   000000 000037
                                                 2   BLANK$COMMON
DTHCMP/MPAL               1   000062 000121      0   000040 000056
                                                 2   BLANK$COMMON
ELAS/MPAL                 1   000122 000202      0   000057 000116
                                                 2   BLANK$COMMON
THCMP/MPAL                1   000203 000262      0   000117 000155
                                                 2   BLANK$COMMON

END OF COLLECTION - TIME 0.206 SECONDS


@HDG,P   ******  MPBR  ******
```

```
@MAP,RS   ME*NASA5.MPBR
MAP 0023-07/13-20:59 -(0,)

    1.NEW   LIB      ME*NASA5.
    2.      CLASS    MPBR
    3.      IN       CPMP,DTHCMP,ELAS,THCMP
    4.      DEF      CPMP,DTHCMP,ELAS,THCMP
    5.      END




      R-OPTION COLLECTION

LENGTHS OF LOCATION COUNTERS ASSIGNED
$(1)  COMBINED ODD COUNTERS     000261  OCTAL       177  DECIMAL
$(2)  COMBINED EVEN COUNTERS    000155  OCTAL       109  DECIMAL
  3   COMMONBLOCK BLANK$COMMON 000000  OCTAL         0  DECIMAL



      COMBINED ELEMENTS

CPMP/MPBR              1    000000 000057       0   000000 000036
                                                2   BLANK$COMMON
DTHCMP/MPBR            1    000060 000117       0   000037 000055
                                                2   BLANK$COMMON
ELAS/MPBR              1    000120 000200       0   000056 000115
                                                2   BLANK$COMMON
THCMP/MPBR             1    000201 000260       0   000116 000154
                                                2   BLANK$COMMON

END OF COLLECTION - TIME 0.192 SECONDS


@HDG,P  ******  MPCU  ******
```

```
****** MPCU ******                                                    DATE 071372      PAGE    1

@MAP,RS   ME*NASA5.MPCU
MAP 0023-07/13-20:59 -(0,)

    1.NEW    LIB        ME*NASA5.

    2.       CLASS      MPCU

    3.       IN         CPMP,DTHCMP,ELAS,THCMP

    4.       DEF        CPMP,DTHCMP,ELAS,THCMP

    5.       END




      R-OPTION COLLECTION


LENGTHS OF LOCATION COUNTERS ASSIGNED
$(1)  COMBINED ODD COUNTERS     000244  OCTAL        164  DECIMAL
$(2)  COMBINED EVEN COUNTERS    000142  OCTAL         98  DECIMAL
  3   COMMONBLOCK BLANK$COMMON  000000  OCTAL          0  DECIMAL



      COMBINED ELEMENTS

CPMP/MPCU                 1    000000 000050       0    000000 000030
                                                   2    BLANK$COMMON
DTHCMP/MPCU               1    000051 000105       0    000031 000045
                                                   2    BLANK$COMMON
ELAS/MPCU                 1    000106 000166       0    000046 000105
                                                   2    BLANK$COMMON
THCMP/MPCU                1    000167 000243       0    000106 000141
                                                   2    BLANK$COMMON

END OF COLLECTION - TIME 0.187 SECONDS


@HDG,P  ******  SCZ93  ******
```

```
@MAP,RS   ME*NASA5.SCZ93
MAP 0023-07/13-20:59 -(0,)

    1.NEW    LIB       ME*NASA5.

    2.       CLASS     SCZ93

    3.       IN        AVGEMT,EMIT

    4.       DEF       AVGEMT,EMIT

    5.       END




      R-OPTION COLLECTION


LENGTHS OF LOCATION COUNTERS ASSIGNED
$(1)   COMBINED ODD COUNTERS     000156  OCTAL      110  DECIMAL
$(2)   COMBINED EVEN COUNTERS    000056  OCTAL       46  DECIMAL
  3    COMMONBLOCK AVGABS        000251  OCTAL      169  DECIMAL
  4    COMMONBLOCK BLANK$COMMON  000000  OCTAL        0  DECIMAL



      COMBINED ELEMENTS

AVGEMT/SCZ93            1   000000 000120       0   000000 000037
                        3   AVGABS              2   BLANK$COMMON
EMIT/SCZ93              1   000121 000155       0   000040 000055
                                                2   BLANK$COMMON

END OF COLLECTION - TIME 0.148 SECONDS



@HDG,P  ******  TBAL  ******
```

```
****** TBAL ******                                                    DATE 071372        PAGE    1

@MAP,RS   ME*NASA5.TBAL
MAP 0023-07/13-21:00 -(0,)

     1.NEW    LIB      ME*NASA5.
     2.       CLASS    TBAL
     3.       IN       CPTB,DTHCTB,THCTB
     4.       DEF      CPTB,DTHCTB,THCTB
     5.       END


     R-OPTION COLLECTION

 LENGTHS OF LOCATION COUNTERS ASSIGNED
 $(1)  COMBINED ODD COUNTERS     000202  OCTAL     130  DECIMAL
 $(2)  COMBINED EVEN COUNTERS    000116  OCTAL      78  DECIMAL
   3   COMMONBLOCK BLANK$COMMON  000000  OCTAL       0  DECIMAL


     COMBINED ELEMENTS

 CPTB/TBAL            1   000000 000061    0   000000 000037
                                           2   BLANK$COMMON
 DTHCTB/TBAL          1   000062 000121    0   000040 000056
                                           2   BLANK$COMMON
 THCTB/TBAL           1   000122 000201    0   000057 000115
                                           2   BLANK$COMMON

 END OF COLLECTION - TIME 0.170 SECONDS


 @HDG,P  ******  TBBR  ******
```

```
@MAP,RS   ME*NASA5.TBBR
MAP 0023-07/13-21:00 -(0,)

    1.NEW   LIB      ME*NASA5.
    2.      CLASS    TBBR
    3.      IN       CPTB,DTHCTB,THCTB
    4.      DEF      CPTB,DTHCTB,THCTB
    5.      END


      R-OPTION COLLECTION

LENGTHS OF LOCATION COUNTERS ASSIGNED
$(1)  COMBINED ODD COUNTERS     000200  OCTAL       128  DECIMAL
$(2)  COMBINED EVEN COUNTERS    000115  OCTAL        77  DECIMAL
  3   COMMONBLOCK BLANK$COMMON  000000  OCTAL         0  DECIMAL


      COMBINED ELEMENTS

CPTB/TBBR              1    000000 000057      0   000000 000036
                                               2   BLANK$COMMON
DTHCTB/TBBR            1    000060 000117      0   000037 000055
                                               2   BLANK$COMMON
THCTB/TBBR             1    000120 000177      0   000056 000114
                                               2   BLANK$COMMON

END OF COLLECTION - TIME 0.167 SECONDS


@HDG,P  ******  TBCU  ******
```

```
@MAP,RS   ME*NASA5.TBCU
MAP 0023-07/13-21:00 -(0,)

    1.NEW   LIB       ME*NASA5.
    2.      CLASS     TBCU
    3.      IN        CPTB,DTHCTB,THCTB
    4.      DEF       CPTB,DTHCTB,THCTB
    5.      END



     R-OPTION COLLECTION

LENGTHS OF LOCATION COUNTERS ASSIGNED
$(1)  COMBINED ODD COUNTERS     000163  OCTAL       115  DECIMAL
$(2)  COMBINED EVEN COUNTERS    000102  OCTAL        66  DECIMAL
  3   COMMONBLOCK BLANK$COMMON 000000  OCTAL         0  DECIMAL



     COMBINED ELEMENTS

CPTB/TBCU               1   000000 000050       0   000000 000030
                                                2   BLANK$COMMON
DTHCTB/TBCU             1   000051 000105       0   000031 000045
                                                2   BLANK$COMMON
THCTB/TBCU              1   000106 000162       0   000046 000101
                                                2   BLANK$COMMON

END OF COLLECTION - TIME 0.165 SECONDS


@PREP     ME*NASA5.
FURPUR 023A-07/13-21:00


@HDG,P  ******  VER1  ******
```

```
@MAP,S    ME*NASA5.VER1
MAP 0023-07/13-21:00 -(0,)

    1.NEW   LIB      ME*NASA5.
    2.      IN       CFSIL,FNAL,MPBR,TBAL,SCZ93
    3.      IN       MAIN
    4.      END

ADDRESS LIMITS    001000 052007    053000 116661
STARTING ADDRESS  046014

WORDS DECIMAL      21000 IBANK      18354 DBANK

              SEGMENT MAIN        001000 052007    053000 116661

NFTV$/FOR         1   001000 001022
NBF00$/FOR                              2   053000 055201
NRBLK$/FOR        1   001023 001045
NBDCV$/FOR        1   001046 001200     2   055202 055237
NSWTC$/FOR        1   001201 001222
NBSBL$/FOR        1   001223 001257
NUPDA$/FOR        1   001260 001312
NWBLK$/FOR        1   001313 001434
NFTCH$/FOR        1   001435 001725     2   055240 055275
NINPT$/FOR        1   001726 002570     2   055276 055315
NOTIN$/FOR        1   002571 003104     2   055316 055321
NOUT$/FOR         1   003105 004073     2   055322 055346
NFMT$/FOR         1   004074 004752     2   055347 055423
NCNVT$/FOR        1   004753 005177     2   055424 055513
NIOER$/FOR        1   005200 005352     2   055514 055620
NININ$/FOR        1   005353 005563     2   055621 055632
NFCHK$/FOR        1   005564 006445     2   055633 055771
                                        4   055772 056043
NWEF$/FOR         1   006446 006647     2   056044 056063
ERU$/MISC
NIAB$/FOR                               2   056064 056122
NEXP5$/FOR        1   006650 006735     2   056123 056132
SINCOS$/FOR       1   006736 007070     2   056133 056154
ATAN$/FOR         1   007071 007274     2   056155 056206
NOSYM$/FOR        1   007275 007534     2   056207 056213
NRWND$/FOR        1   007535 007614     2   056214 056225
NEXP6$/FOR        1   007615 010011     2   056226 056277
NBKSP$/FOR        1   010012 010510     2   056300 056326
```

EXP$/FOR	1	010511 010600	2	056327 056347
ALOG$/FOR	1	010601 010720	2	056350 056410
NERR$/FOR	1	010721 011245	2	056411 056554
ASINCOS$/FOR	1	011246 011462	0	056555 056602
SQRT$/FOR	1	011463 011523	2	056603 056614
NLOUT$/FOR	1	011524 012606	2	056615 056652
NFOUT$/FOR	1	012607 013117	2	056653 056674
NFINP$/FOR	1	013120 013433	2	056675 056761
NIBUF$/FOR	1	013434 013476	2	056762 056762
NIER$/FOR	1	013477 013560	2	056763 057116
NOBUF$/FOR	1	013561 013625		
NLINP$/FOR	1	013626 015341	2	057117 057300
TIR$/TECH	1	015342 016026	0	057301 057331
			2	057332 057611
NCLOS$/FOR	1	016027 016175	2	057612 057643
TTIP	1	016176 016255	0	057644 057744
			2	BLANK$COMMON
EFFICY	1	016256 016436	0	057745 060075
			2	BLANK$COMMON
DEFNT	1	016437 016516	0	060076 060120
			2	BLANK$COMMON
EXITAV	1	016517 016626	0	060121 060150
	3	QRD	2	BLANK$COMMON
	5	ABSRST	4	QIN
MTXINV	1	016627 017034	0	060151 060207
	3	QRD	2	BLANK$COMMON
TRMATX	1	017035 017331	0	060210 060260
	3	QRD	2	BLANK$COMMON
			4	ABSRST
ABSORB	1	017332 020131	0	060261 060375
	3	QRD	2	BLANK$COMMON
	5	AVGABS	4	ABSRST
INTERP	1	020132 020357	0	060376 060460
			2	BLANK$COMMON
NUS	1	020360 021221	0	060461 060574
			2	BLANK$COMMON
REFP	1	021222 021610	0	060575 060757
			2	BLANK$COMMON
CPAIR	1	021611 021720	0	060760 061014
			2	BLANK$COMMON
TNH	1	021721 022004	0	061015 061044
			2	BLANK$COMMON
ENTAIR	1	022005 022231	0	061045 061135
			2	BLANK$COMMON
ATMOS	1	022232 022512	0	061136 061346
			2	BLANK$COMMON
ALTVEL	1	022513 022721	0	061347 061364
			2	BLANK$COMMON
RKSF	1	022722 023761	0	061365 061450
			2	BLANK$COMMON
TRNSPT	1	023762 024152	0	061451 061510
			2	BLANK$COMMON
DRVLCN (COMMON BLOCK)				061511 061511
DRVLCM (COMMON BLOCK)				061512 061535
CNTLN	1	024153 024263	0	061536 061560
	3	DRVLCM	2	BLANK$COMMON
			4	DRVLCN

```
DERIVL                     1   024264 024542       0   061561 061633
                           3   FLCMP               2   BLANK$COMMON
FMINV                      1   024543 025050       0   061634 063113
                                                   2   BLANK$COMMON
PDERIV                     1   025051 025254       0   063114 063133
                           3   ADBH                2   BLANK$COMMON
TTIPS                      1   025255 025642       0   063134 063243
                           3   ADBH                2   BLANK$COMMON
                                                   4   QIN
NUSA                       1   025643 025745       0   063244 063267
                                                   2   BLANK$COMMON
SHADE                      1   025746 026051       0   063270 063312
                                                   2   BLANK$COMMON
FINT                       1   026052 026162       0   063313 063341
                                                   2   BLANK$COMMON
YINT                       1   026163 026477       0   063342 063477
                                                   2   BLANK$COMMON
D2DX2                      1   026500 026662       0   063500 063545
                                                   2   BLANK$COMMON
DDX                        1   026663 027035       0   063546 063613
                                                   2   BLANK$COMMON
QRAD                       1   027036 030050       0   063614 064712
                           3   QRD                 2   BLANK$COMMON
                           5   ABSRST              4   QIN
                           7   AVGABS              6   SSF
CONVEC                     1   030051 030631       0   064713 065056
                           3   VELALT              2   BLANK$COMMON
                           5   SRTCNV              4   CNV
                           7   SSF                 6   QRD
POLY                       1   030632 030675       0   065057 065073
                                                   2   BLANK$COMMON
RKS                        1   030676 031735       0   065074 065157
                                                   2   BLANK$COMMON
SHAPEF                     1   031736 032772       0   065160 065331
                           3   QRD                 2   BLANK$COMMON
                                                   4   SSF
DEFINT                     1   032773 033217       0   065332 065377
                                                   2   BLANK$COMMON
FLCMP (COMMON BLOCK)                                   065400 065423
FLSTRT                     1   033220 033464       0   065424 065656
                           3   DVCMFL              2   BLANK$COMMON
                                                   4   FLCMP
TK                         1   033465 033731       0   065657 065740
                                                   2   BLANK$COMMON
QINCID                     1   033732 034760       0   065741 066625
                           3   QIN                 2   BLANK$COMMON
                                                   4   TC
ADIABH                     1   034761 035502       0   066626 067276
                           3   ADBH                2   BLANK$COMMON
TCALC                      1   035503 036354       0   067277 070166
                           3   ADBH                2   BLANK$COMMON
                           5   QIN                 4   TC
SRTCNV (COMMON BLOCK)                                  070167 070171
CNTLM                      1   036355 040434       0   070172 073614
                           3   SRTCNV              2   BLANK$COMMON
                           5   QIN                 4   QRD
                           7   FLDINL              6   GEOM
```

```
                                                       8   DVCMFL
DERIVM                      1   040435 043014          0   073615 074675
                            3   DVM                    2   BLANK$COMMON
                            5   FLDINL                 4   QIN
                                                       6   DVCMFL
AVGABS (COMMON BLOCK)                                      074676 075146
DVCMFL (COMMON BLOCK)                                      075147 075150
FLDINL (COMMON BLOCK)                                      075151 075627
GEOM (COMMON BLOCK)                                        075630 075647
SSF (COMMON BLOCK)                                         075650 075657
ABSRST (COMMON BLOCK)                                      075660 076460
TC (COMMON BLOCK)                                          076461 076522
QIN (COMMON BLOCK)                                         076523 100332
QRD (COMMON BLOCK)                                         100333 104253
CNV (COMMON BLOCK)                                         104254 104263
VELALT (COMMON BLOCK)                                      104264 105415
DVM (COMMON BLOCK)                                         105416 105417
ADBH (COMMON BLOCK)                                        105420 105771
BLANK$COMMON (COMMON BLOCK)                                105772 107106
CFSIL                       1   043015 044750          2   107107 110025
                            3   BLANK$COMMON
FNAL                        1   044751 045152          2   110026 110143
                            3   BLANK$COMMON
MPBR                        1   045153 045433          2   110144 110320
                            3   BLANK$COMMON
TBAL                        1   045434 045635          2   110321 110436
                            3   BLANK$COMMON
SCZ93                       1   045636 046013          2   110437 110514
                            3   AVGABS                 4   BLANK$COMMON
MAIN                        1   046014 052007          0   110515 116661
                            3   ADBH                   2   BLANK$COMMON
                            5   VELALT                 4   DVM
                            7   QRD                    6   CNV
                            9   TC                     8   QIN
                           11   SSF                   10   ABSRST
                           13   FLDINL                12   GEOM
                                                      14   DVCMFL

SYS$*RLIB$. LEVEL 63
END OF COLLECTION - TIME 4.525 SECONDS


QHDG,P  ******  TABLE OF CONTENTS  ******.L,1
```

****** TABLE OF CONTENTS ****** DATE 071372 PAGE 1

@PRT,T ME*NASA5.
FURPUR 023A-07/13-21:00

ME*NASA5 ELEMENT TABLE

D	NAME	VERSION	TYPE	DATE	TIME	SEQ #	SIZE-PRE,TEXT	(CYCLE	WORD)	PSRMODE	LOCATION
	ABSORB		FOR SYMB	09 MAY 72	16:50:13	1	21	5	0	1	1792
	ADIABH		FOR SYMB	02 MAY 72	15:31:15	2	24	5	0	1	1813
	ALTVEL		FOR SYMB	09 MAY 72	16:50:24	3	7	5	0	1	1837
	ATMOS		FOR SYMB	09 MAY 72	16:50:26	4	24	5	0	1	1844
	AVGEMT	SCZ93	FOR SYMB	09 MAY 72	15:48:01	5	8	5	0	1	1868
	BETA	CFFC43	FOR SYMB	09 MAY 72	16:43:19	6	3	5	0	1	1876
	BETA	CFFC75	FOR SYMB	09 MAY 72	16:44:12	7	3	5	0	1	1879
	BETA	CFHE	FOR SYMB	09 MAY 72	16:40:41	8	6	5	0	1	1882
	BETA	CFNAK	FOR SYMB	09 MAY 72	16:42:30	9	3	5	0	1	1888
	BETA	CFSIL	FOR SYMB	30 JUN 72	15:44:49	10	8	5	0	1	1891
	CAPPA	CFFC43	FOR SYMB	09 MAY 72	16:43:25	11	3	5	0	1	1899
	CAPPA	CFFC75	FOR SYMB	09 MAY 72	16:44:34	12	3	5	0	1	1902
	CAPPA	CFHE	FOR SYMB	09 MAY 72	16:40:48	13	5	5	0	1	1905
	CAPPA	CFNAK	FOR SYMB	09 MAY 72	16:42:37	14	5	5	0	1	1910
	CAPPA	CFSIL	FOR SYMB	30 JUN 72	15:44:52	15	7	5	0	1	1915
	CFFC43		MAP SYMB	10 MAY 72	08:56:52	16	1	5	0	1	1922
	CFFC75		MAP SYMB	10 MAY 72	08:57:18	17	1	5	0	1	1923
	CFHE		MAP SYMB	10 MAY 72	08:58:15	18	1	5	0	1	1924
	CFNAK		MAP SYMB	10 MAY 72	08:58:40	19	1	5	0	1	1925
	CFSIL		MAP SYMB	10 MAY 72	08:59:02	20	1	5	0	1	1926
	CNTLM		FOR SYMB	12 MAY 72	09:06:54	21	77	5	0	1	1927
	CNTLN		FOR SYMB	09 MAY 72	16:49:43	22	12	5	0	1	2004
	CONVEC		FOR SYMB	09 MAY 72	16:51:04	23	28	5	0	1	2016
	CPAIR		FOR SYMB	09 MAY 72	16:50:38	24	6	5	0	1	2044
	CPF	CFFC43	FOR SYMB	09 MAY 72	16:43:31	25	3	5	0	1	2050
	CPF	CFFC75	FOR SYMB	09 MAY 72	16:44:44	26	3	5	0	1	2053
	CPF	CFHE	FOR SYMB	09 MAY 72	16:40:55	27	5	5	0	1	2056
	CPF	CFNAK	FOR SYMB	09 MAY 72	16:42:43	28	5	5	0	1	2061
	CPF	CFSIL	FOR SYMB	30 JUN 72	15:44:54	29	13	5	0	1	2066
	CPFN	FNAL	FOR SYMB	09 MAY 72	16:47:50	30	5	5	0	1	2079
	CPFN	FNBR	FOR SYMB	09 MAY 72	16:48:28	31	5	5	0	1	2084
	CPFN	FNCU	FOR SYMB	09 MAY 72	16:48:13	32	4	5	0	1	2089
	CPMP	MPAL	FOR SYMB	09 MAY 72	16:48:38	33	5	5	0	1	2093
	CPMP	MPBR	FOR SYMB	09 MAY 72	16:49:21	34	5	5	0	1	2098
	CPMP	MPCU	FOR SYMB	09 MAY 72	16:48:52	35	4	5	0	1	2103
	CPTB	TBAL	FOR SYMB	09 MAY 72	16:46:59	36	5	5	0	1	2107
	CPTB	TBBR	FOR SYMB	09 MAY 72	16:47:32	37	5	5	0	1	2112
	CPTB	TBCU	FOR SYMB	09 MAY 72	16:47:18	38	4	5	0	1	2117
	DATA		ELT SYMB	09 MAY 72	14:02:46	39	24	5	0	1	2121
	DDX		FOR SYMB	09 MAY 72	16:51:51	40	8	5	0	1	2145
	DEFINT		FOR SYMB	09 MAY 72	16:52:40	41	6	5	0	1	2153
	DEFNT		FOR SYMB	09 MAY 72	16:52:04	42	3	5	0	1	2159
	DERIVL		FOR SYMB	11 MAY 72	15:27:24	43	18	5	0	1	2162
	DERIVM		FOR SYMB	09 MAY 72	16:52:10	44	61	5	0	1	2180
	DTHCFN	FNAL	FOR SYMB	09 MAY 72	16:47:46	45	4	5	0	1	2241
	DTHCFN	FNBR	FOR SYMB	09 MAY 72	16:48:23	46	4	5	0	1	2245
	DTHCFN	FNCU	FOR SYMB	09 MAY 72	16:48:10	47	4	5	0	1	2249
	DTHCMP	MPAL	FOR SYMB	09 MAY 72	16:48:35	48	4	5	0	1	2253
	DTHCMP	MPBR	FOR SYMB	09 MAY 72	16:49:13	49	4	5	0	1	2257
	DTHCMP	MPCU	FOR SYMB	09 MAY 72	16:48:49	50	4	5	0	1	2261
	DTHCTB	TBAL	FOR SYMB	09 MAY 72	16:46:53	51	4	5	0	1	2265

THCFN	FNBR	FOR SYMB	09 MAY 72	16:48:17	109		5	5	0	1	2991
THCFN	FNCU	FOR SYMB	09 MAY 72	16:47:57	110		5	5	0	1	2996
THCMP	MPAL	FOR SYMB	09 MAY 72	16:48:33	111		5	5	0	1	3001
THCMP	MPBR	FOR SYMB	09 MAY 72	16:48:57	112		5	5	0	1	3006
THCMP	MPCU	FOR SYMB	09 MAY 72	16:48:44	113		5	5	0	1	3011
THCTB	TBAL	FOR SYMB	09 MAY 72	16:46:49	114		5	5	0	1	3016
THCTB	TBBR	FOR SYMB	09 MAY 72	16:47:24	115		5	5	0	1	3021
THCTB	TBCU	FOR SYMB	09 MAY 72	16:47:04	116		5	5	0	1	3026
TK		FOR SYMB	09 MAY 72	16:51:09	117		7	5	0	1	3031
TNH		FOR SYMB	09 MAY 72	16:50:50	118		4	5	0	1	3038
TRMATX		FOR SYMB	09 MAY 72	16:50:04	119		11	5	0	1	3042
TRNSPT		FOR SYMB	09 MAY 72	16:52:30	120		11	5	0	1	3053
TTIP		FOR SYMB	23 MAR 72	16:33:46	121		5	5	0	1	3064
TTIPS		FOR SYMB	02 MAY 72	15:37:06	122		15	5	0	1	3069
VER1		MAP SYMB	10 MAY 72	16:52:30	123		1	5	0	1	3084
VISC	CFFC43	FOR SYMB	09 MAY 72	16:43:41	124		4	5	0	1	3085
VISC	CFFC75	FOR SYMB	09 MAY 72	16:45:47	125		4	5	0	1	3089
VISC	CFHE	FOR SYMB	09 MAY 72	16:41:03	126		3	5	0	1	3093
VISC	CFNAK	FOR SYMB	09 MAY 72	16:42:52	127		4	5	0	1	3096
VISC	CFSIL	FOR SYMB	30 JUN 72	15:44:58	128		5	5	0	1	3100
YINT		FOR SYMB	09 MAY 72	16:28:50	129		10	5	0	1	3105
ABSORB		RELOCATABLE	13 JUL 72	20:52:57	130	2	22				3115
ADIABH		RELOCATABLE	13 JUL 72	20:53:00	131	2	27				3139
ALTVEL		RELOCATABLE	13 JUL 72	20:53:02	132	1	7				3168
ATMOS		RELOCATABLE	13 JUL 72	20:53:04	133	1	16				3176
AVGEMT	SCZ92	RELOCATABLE	13 JUL 72	20:53:06	134	1	6				3193
BETA	CFFC43	RELOCATABLE	13 JUL 72	20:53:09	135	1	2				3200
BETA	CFFC75	RELOCATABLE	13 JUL 72	20:53:10	136	1	2				3203
BETA	CFHE	RELOCATABLE	13 JUL 72	20:53:12	137	1	5				3206
BETA	CFNAK	RELOCATABLE	13 JUL 72	20:53:14	138	1	2				3212
BETA	CFSIL	RELOCATABLE	13 JUL 72	20:53:16	139	1	10				3215
CAPPA	CFFC43	RELOCATABLE	13 JUL 72	20:53:18	140	1	1				3226
CAPPA	CFFC75	RELOCATABLE	13 JUL 72	20:53:21	141	1	1				3228
CAPPA	CFHE	RELOCATABLE	13 JUL 72	20:53:24	142	1	4				3230
CAPPA	CFNAK	RELOCATABLE	13 JUL 72	20:53:28	143	1	4				3235
CAPPA	CFSIL	RELOCATABLE	13 JUL 72	20:54:16	144	1	8				3240
CNTLM		RELOCATABLE	13 JUL 72	20:54:25	145	3	78				3249
CNTLN		RELOCATABLE	13 JUL 72	20:54:31	146	2	5				3330
CONVEC		RELOCATABLE	13 JUL 72	20:54:37	147	3	22				3337
CPAIR		RELOCATABLE	13 JUL 72	20:54:40	148	1	6				3362
CPF	CFFC43	RELOCATABLE	13 JUL 72	20:54:42	149	1	2				3369
CPF	CFFC75	RELOCATABLE	13 JUL 72	20:54:45	150	1	2				3372
CPF	CFHE	RELOCATABLE	13 JUL 72	20:54:46	151	1	5				3375
CPF	CFNAK	RELOCATABLE	13 JUL 72	20:54:49	152	1	5				3381
CPF	CFSIL	RELOCATABLE	13 JUL 72	20:54:53	153	1	17				3387
CPFN	FNAL	RELOCATABLE	13 JUL 72	20:54:56	154	1	5				3405
CPFN	FNBR	RELOCATABLE	13 JUL 72	20:54:58	155	1	5				3411
CPFN	FNCU	RELOCATABLE	13 JUL 72	20:55:00	156	1	4				3417
CPMP	MPAL	RELOCATABLE	13 JUL 72	20:55:02	157	1	5				3422
CPMP	MPBR	RELOCATABLE	13 JUL 72	20:55:05	158	1	5				3428
CPMP	MPCU	RELOCATABLE	13 JUL 72	20:55:07	159	1	4				3434
CPTB	TBAL	RELOCATABLE	13 JUL 72	20:55:10	160	1	5				3439
CPTB	TBBR	RELOCATABLE	13 JUL 72	20:55:12	161	1	5				3445
CPTB	TBCU	RELOCATABLE	13 JUL 72	20:55:14	162	1	4				3451
DDX		RELOCATABLE	13 JUL 72	20:55:16	163	1	7				3456
DEFINT		RELOCATABLE	13 JUL 72	20:55:21	164	1	9				3464
DEFNT		RELOCATABLE	13 JUL 72	20:55:24	165	1	3				3474

THCFN	FNCU	RELOCATABLE	13 JUL 72	20:58:31	223	1	4	4241
THCMP	MPAL	RELOCATABLE	13 JUL 72	20:58:33	224	1	5	4246
THCMP	MPBR	RELOCATABLE	13 JUL 72	20:58:36	225	1	5	4252
THCMP	MPCU	RELOCATABLE	13 JUL 72	20:58:38	226	1	4	4258
THCTB	TBAL	RELOCATABLE	13 JUL 72	20:58:41	227	1	5	4263
THCTB	TBBR	RELOCATABLE	13 JUL 72	20:58:43	228	1	5	4269
THCTB	TBCU	RELOCATABLE	13 JUL 72	20:58:45	229	1	4	4275
TK		RELOCATABLE	13 JUL 72	20:58:48	230	2	11	4280
TNH		RELOCATABLE	13 JUL 72	20:58:49	231	1	4	4293
TRMATX		RELOCATABLE	13 JUL 72	20:58:52	232	1	11	4298
TRNSPT		RELOCATABLE	13 JUL 72	20:58:55	233	1	8	4310
TTIP		RELOCATABLE	13 JUL 72	20:58:57	234	1	5	4319
TTIPS		RELOCATABLE	13 JUL 72	20:59:00	235	2	16	4325
VISC	CFFC43	RELOCATABLE	13 JUL 72	20:59:02	236	1	3	4343
VISC	CFFC75	RELOCATABLE	13 JUL 72	20:59:04	237	1	3	4347
VISC	CFHE	RELOCATABLE	13 JUL 72	20:59:06	238	1	2	4351
VISC	CFNAK	RELOCATABLE	13 JUL 72	20:59:09	239	1	2	4354
VISC	CFSIL	RELOCATABLE	13 JUL 72	20:59:10	240	1	5	4357
YINT		RELOCATABLE	13 JUL 72	20:59:13	241	1	13	4363
CFFC43		RELOCATABLE	13 JUL 72	20:59:27	242	2	10	4377
CFFC75		RELOCATABLE	13 JUL 72	20:59:29	243	2	10	4389
CFHE		RELOCATABLE	13 JUL 72	20:59:32	244	2	28	4401
CFNAK		RELOCATABLE	13 JUL 72	20:59:36	245	2	23	4431
CFSIL		RELOCATABLE	13 JUL 72	20:59:39	246	3	69	4456
FNAL		RELOCATABLE	13 JUL 72	20:59:43	247	2	11	4528
FNBR		RELOCATABLE	13 JUL 72	20:59:45	248	2	11	4541
FNCU		RELOCATABLE	13 JUL 72	20:59:48	249	2	10	4554
MPAL		RELOCATABLE	13 JUL 72	20:59:50	250	2	15	4566
MPBR		RELOCATABLE	13 JUL 72	20:59:53	251	2	15	4583
MPCU		RELOCATABLE	13 JUL 72	20:59:55	252	2	14	4600
SCZ93		RELOCATABLE	13 JUL 72	20:59:58	253	2	8	4616
TBAL		RELOCATABLE	13 JUL 72	21:00:01	254	2	11	4626
TBBR		RELOCATABLE	13 JUL 72	21:00:03	255	2	11	4639
TBCU		RELOCATABLE	13 JUL 72	21:00:06	256	2	10	4652
VER1		ABSOLUTE	13 JUL 72	21:00:45	257		948	4664
NEXT AVAILABLE LOCATION-								5612

ASSEMBLER PROCEDURE TABLE EMPTY

COBOL PROCEDURE TABLE EMPTY

FORTRAN PROCEDURE TABLE EMPTY

ENTRY POINT TABLE

D NAME	LINK	D NAME	LINK	D NAME	LINK	D NAME	LINK	D NAME	LINK
ABSORB	130	ADIABH	131	ALTVEL	132	ATMOS	133	AVGEMT	253
AVGEMT	134	BETA	135	BETA	136	BETA	137	BETA	138
BETA	139	BETA	246	BETA	245	BETA	244	BETA	243
BETA	242	CAPPA	140	CAPPA	246	CAPPA	141	CAPPA	245
CAPPA	142	CAPPA	244	CAPPA	143	CAPPA	243	CAPPA	144
CAPPA	242	CNTLM	145	CNTLN	146	CONVEC	147	CPAIR	148
CPF	246	CPF	245	CPF	149	CPF	150	CPF	244
CPF	151	CPF	152	CPF	243	CPF	153	CPF	242
CPFN	249	CPFN	248	CPFN	247	CPFN	154	CPFN	155
CPFN	156	CPMP	157	CPMP	252	CPMP	251	CPMP	250
CPMP	158	CPMP	159	CPTB	256	CPTB	255	CPTB	254

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GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering
Atlanta, Georgia

Final Report
Part 3

SPACE RADIATOR SIMULATION

SYSTEM ANALYSIS

Contract No. NAS 9-10415

by
William Z. Black and Wolfgang Wulff

Sponsored by the
Power Generation Branch
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FOREWORD

This report covers the results of one portion of a two year research project carried out by the School of Mechanical Engineering at the Georgia Institute of Technology, Atlanta, Georgia for the NASA Manned Spacecraft Center, Houston, Texas, under Contract No. NAS 9-10415. This report summarize the results of the radiator simulation analysis. The users manual for the execution of the computer program resulting from the analysis in this report is contained in a separate report. A third report covers the development of a simplified system simulation and the initial phases of a system optimization procedure. The project title is "Study of Design Parameters of Space Base and Space Shuttle Heat Rejection Systems." The work reported here was monitored by Dr. W. E. Simon of the Power Generation Branch of NASA MSC, Houston, Texas, and was carried out by Dr. W. Z. Black and Dr. W. Wulff as Co-Investigators and Mr. S. M. Morcos, Mr. S. L. Yao, and Mr. R. M. Hinson graduate students in the School of Mechanical Engineering under the direction of Dr. S. P. Kezios.

The work carried out by Dr. W. Z. Black is reflected in the analysis of Part II, Chapters 2, 7, 8, 11 and 14. Dr. Wulff is responsible for the analysis of Part II, Chapters 1 and 3 through 6, Chapters 9, 10, 12 and 13 as well as the numerical analysis in Part III. Mr. Morcos completed the property analysis reported in the Appendices A and B. Mr. Yao completed the surface coating property and the shape factor analysis reported in Appendices C and D, respectively.

SUMMARY

A transient heat transfer analysis was carried out on a space radiator heat rejection system exposed to an arbitrarily prescribed combination of aerodynamic heating, solar, albedo and planetary irradiation. A rigorous analysis was carried out for the radiation panel and tubes lying in one plane and an approximate analysis was used to extend the rigorous analysis to the case of a curved panel. For the rigorous analysis the radiator system consists of equally spaced parallel coolant flow channels, all in one plane and connected by plane fin panels of trapezoidal cross-section, symmetric with respect to two normal planes, one passing through the tube axis, the other through the center between adjacent tubes. Investigated was one typical tube-fin element and the result extended over the entire system, on the basis of the above symmetry.

The rigorous analysis was extended, by approximate methods, to include radiator system which do not conform to the above symmetry restrictions. As a result, radiator systems can be treated whose coolant flow channels do not lie in one plane, provided that the radiative interaction between neighboring tube-fin elements is small when compared with the radiant flux densitites at the panel. Moreover, radiator systems with non-uniform irradiation, non-uniform coolant inlet conditions and U-shaped coolant channels can be treated, provided that the spacing between channels is small when compared with the channel length.

The analysis permits the consideration of both gaseous and liquid coolant fluids, including liquid metals, under prescribed, time-dependent inlet conditions. The flow channels are covered with the same passive thermal control coating with optically diffuse but wavelength and temperature dependent optical properties.

The major results of the analysis are the prediction of both transient and steady-state, two-dimensional temperature profiles, the local and total heat rejection rates, the coolant flow pressure drop in the flow channel, and the total system weight and the protection layer thickness.

A computer program consisting of 62 program units was coded to execute the numerical solution of the system of differantial equations

occurring in the analysis and to predict principal design parameters. The modular program structure readily permits later modifications. A separate final report entitled "Space Radiator Simulation, Manual for Computer Program" has been prepared which describes the computer programs [29].

A simplified analysis was carried out to aid the detailed analysis and to serve as the basis of systematic optimization. This analysis is covered in a companion report, entitled "Simplified Analysis and Optimization of Space Base and Space Shuttle Heat Rejection Systems" [30]. Regarding the heat rejection rates, its results are, for the test cases carried out so far, within 4% in agreement with the results of the detailed analysis. However, this rigorous analysis has greater applicability and detail.

This engineering analysis report is one of three final reports. The other two reports are a user's manual describing the computer code of this extensive, rigorous analysis [29] and the final report covering the simplified radiator system analyses and system optimization which describe both analysis and computer codes [30].

This report is written in two principal parts. The analysis and the governing equations are contained in the first part, Chapter II, titled Analysis. The numerical techniques are covered in Chapter III. Details which the reader may need to expand the program are placed in the appendices.

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NOMENCLATURE

a	empirical constant used to account for spalling of protection layer (Eq. 8.8)	
a	function of temperature, used to express the isothermal compressibility and the zero-pressure isobaric thermal expansion coefficient, see also b and c (Eq. 12.9)	
a_z	axial fluid flow acceleration	ft/sec^2
A	area	ft^2
A_n	coefficients in polynomial for atmospheric pressure at high altitudes (Eq. 14.8)	-
A_s	surface area	ft^2
A_x	cross-sectional area perpendicular to x coordinate	ft^2
A_z	cross-sectional area perpendicular to z coordinate	ft^2
b	defined in Eq. 12.9, see also a	
B	fin geometrical parameter (Eq. 2.14)	-
B_N	coefficients in polynomial for atmospheric density at high altitudes (Eq. 14.8)	-
c	atmospheric speed of sound	ft/sec
c	negative slope of fin sides	-
c	defined in Eq. 12.9, see also a	
c	speed of light	ft/sec
$\bar{c}$	speed of sound in meteoroid protection material	ft/sec
c_p	specific heat at constant pressure	Btu/(slug R)
c_v	specific heat at constant volume	Btu/(slug R)

c_v	zero-pressure specific heat at constant volume	Btu/(slug R)
d	diameter of meteoroid particle	in
d	tube diameter	ft
D	fin geometrical parameter (Eq. 2.15)	-
E	emissive power	Btu/(hr ft^2)
E	modulus of elasticity	lbf/in^2
E	relative error	-
f	Fanning friction factor	-
F	cumulative meteoroid flux (eq. 8.4)	1/(ft^2 day)
F	dimensionless parameter, Eqs. 3.31-34	
g_c	32.174 ft lbm/(lbf sec^2)	
h	Plank's constant, h = 6.625 x 10^{-34} W s^2	
h	specific enthalpy	Btu/slug
H	geopotential altitude	ft
H	fin height, from root to tip	ft
h_c	convective film coefficient	Btu/(hr ft^{2}R)
h_i	convective heat transfer coefficient used in reference enthalpy method	lbm/(hr ft^2)
k	Boltzmann constant, k = 1.380 x 10^{-23} Ws/K	
k	thermal conductivity	Btu/(hr ft R)
L	temperature gradient in atmosphere (Table 4)	(K/km)
L	tube (and fin) length	ft
M	Mach number of orbiter	-
M	mass	slug
M	molecular weight	-
M_{ij}	transfer matrix Eq. 6.19	

M_m	inverted M	-
M	defined by Eq. 10.22	
n	constant that describes depth of penetration as a function of angle of incidence (Eq. 8.6)	-
n	number of tubes	
n	refractive index	-
N	cumulative number of meteoroid impacts	-
N_{Bi}	Biot number	-
N_{Fo}	Fourier number	-
N_{Gr}	Grashof number	-
N_{Nc}	Conductance parameter	-
N_{Nu}	Nusselt number	-
N_{Re}	Reynolds number	-
N_{Pr}	Prandtl number	-
p	absolute pressure	lbf/ft^2
p_j	nondimensional exitation vector, Eq. 6.21	-
P_j	excitation vector, Eq. 6.18	
P_o	probability of no damage due to meteoroid impact	-
P_∞	depth of penetration of a meteoroid particle into an infinite target.	in
q"	heat flux	Btu/(hr ft^2)
$\tilde{q}$	nondimensional heat flux	-
$\bar{Q}_o$	nondimensional inlet power flux	-
$\bar{Q}_{rad}$	defined by Eq. 10.21	-
r,z	polar coordinates, see Fig. 1	ft
r	recovery factor	-

R^*	universal gas constant	ft lbf/(lb mole R)
R	outer meteoroid protection layer radius	ft
s	thickness	ft
$s_f = \frac{s_r}{2}$	fin half thickness at root	ft
$\bar{s}_f$	normalized fin thickness (Eq. 2.13)	-
$\overline{s_i s_j}$	direct exchange area (Eq. 6.1)	ft^2
S	constant in atmospheric viscosity equation (Eq. 3.7)	K
SS	direct exchange "area", partially evaluated	ft
t	time	hr
T	absolute temperature	R
u	specific interval energy	Btu/slug
V	velocity of orbiter	ft/sec
$\bar{V}$	velocity of meteoroid relative to radiator	ft/sec
w	coolant flow velocity	ft/sec
w_j	nondimensional radiosity, Eq. 6.21	-
W_j	radiosity	Btu/(hr ft^2)
x	distance from orbiter stagnation point to radiator panel	ft
x, z	rect. Cart. coordinates, see Fig. 1	ft
x_{ij}, x_{ijk}	auxiliary parameters, defined by Eqs. 6.10 and 6.11	-
y	overall length of radiator in direction parallel to gravity	ft
y	transverse fin coordinate	ft
z	axial distance	ft
Z	geometric altitude	ft

Greek Symbols

α	experimental meteoroid flux parameter, (Eq. 8.4)	$1/(ft^2 day\ gm^{\beta})$
α	thermal diffusivity	ft^2/hr
α_{ij}	total hemispherical absorptance	-
β	constant in atmospheric viscosity equation, (Eq. 3.7)	$kg/(sec\ mK^{1/2})$
β	experimental meteoroid flux parameter, (Eq. 8.4)	-
β	isobaric thermal expansion coefficient, see Eq. 3.5	1/R
γ	ratio of specific heats	-
δ	diameter-over-length ratio	-
δ_{ij}	Kronecker delta	-
ϵ	total hemisphere emittance	-
ζ	dimensionless axial distance, Eq. 3.19	-
η	dimensionless radius, Eq. 3.25	-
θ	dimensionless temperature, Eq. 3.21	-
θ	empirical constant (Eq. 8.1)	-
κ	isothermal compressibility, Eq. 3.4	ft^2/lbf
λ	angle between path of meteoroid and normal to protected surface (Eq. 8.6)	deg.
λ	wave length	ft
λ_1	parameter, defined by Eq. 4.11	-
λ_2	parameter, defined by Eq. 4.12	-
μ	dynamic viscosity	slug/(ft sec)
ν	dimensionless density	-
ν	kinematic viscosity	ft^2/sec
ξ	dimensionless x coordinate	-

π	dimensionless pressure, Eq. 3.22	
ρ	density	slug/ft^3
σ	Stefan-Boltzmann constant	Btu/(hr ft^2 R^4)
τ	dimensionless time, Eq. 3.20	-
τ	time radiator is exposed to meteoroid environment	day
ϕ	angle between surface normal and radiation beam	-
ϕ	dimensionless property Eqs. 3.27-3.30, Eq. 4.4	-
ϕ,ϕ^*	polar angle in Eq. 6.15	-
ϕ_{Nc}	modified conduction parameter, Eq. 5.6	
ϕ	empirical constant (Eq. 8.1)	-
χ	quadrature coefficient	-
ψ	circumferential fraction, defined by Eq. 4.3	-
ψ	residual, see Eqs. 12.1 and 12.2	-
ω	dimensionless velocity Eq. 3.23	-

Subscripts

aw	adiabatic wall
aero	aerodynamic
b	values at the endpoints of straight line segments of atmospheric temperature profile, (Table 4)
c	coolant fluid
c	critical value
c	enclosure
c_p	referring to specific heat at constant pressure

e	outer surface of meteoroid protection layer, (environment)
f	referring to friction factor
f	fin
F	Fourier number
i, j	position index
m	meteoroid protection layer
M	Mach number
net,rad	net radiant
p	meteoroid particle
p	referring to pressure
r	fin root
t	fin tip
t	target material
t	tubes
w	channel wall
w	surface or wall condition
z	axial distance
z	thermal equation of state
o	entrance (reference) conditions
o	sea level values
1	upper fin side
2	lower fin side
∞	free stream condition
ζ	partial differentiation with resp. to ζ
η	partial differentiation with resp. to η
κ	referring to compressibility

λ monochromatic

τ partial differentiation with respect to τ

Superscripts

* evaluated at reference temperature T*

I. OBJECTIVE

The purpose of the analysis presented here is to develop a radiator system simulation which serves (i) to provide the design parameters necessary for the development of the radiator system, (ii) to predict the transient radiator performance under prescribed environmental and operation conditions, (iii) to predict the system response to conditions which lead to coolant fluid temperatures outside their operational temperature range, and (iv) to use the system performance data to suggest design options for shuttle radiator panel.

The class of system analyzed here is described in the following section. The system parameters produced for design purposes are those which describe coolant fluid flow field and the thermal state of the radiator structures as well as the geometry and the weight of the system components.

The arbitrarily prescribed environmental conditions consist of the specification of ascent and reentry profiles and of solar, planetary and albedo irradiation as a function of time.

The prescribed operating conditions are the coolant fluid inlet properties.

The analysis is designed to accommodate spectral characteristics of surface coatings, specified as functions of temperature. The analysis is, however, restricted to optically diffuse coatings.

Both coolant and structural material properties are accepted as prescribed functions of temperature. Coolant properties are specified as functions of pressure or density as well as temperature.

The analysis serves as the basis for a large-scale computer code in modular form. Material properties, complex mathematical operations and readily identifiable tasks in the computer code are written as subprograms.

The computer code is designed to simulate space radiator heat rejection systems during ascent, reentry and mission phases of the spacecraft and to optimize the radiator system configuration via enumeration of parameter sets.

The Analysis is covered in the following chapter. The numerical techniques employed are discussed in Chapter III, while the preparation for the program units describing material properties is deferred to the Appendices.

The computer code is described in a separate manual [29].

When the contract began over two years ago, the emphasis on radiator design was primarily on the space base heat rejection system. Since that time, the emphasis has shifted so that it is now heavily placed on the shuttle vehicle. Furthermore, the responsibility of developing the heat rejection system has been shifted from the Power Generation Branch and the design philoso has changed to an integrated system which includes waste heat from sources other than the power generation system which was anticipated as the sole source of waste heat when the contract began. Due to the shift in design philosophy, the report will not recommend detailed design considerations, although once heat loads from other sources are known, the analysis presented here can be used to aid in the design of an integrated radiator system.

II. ANALYSIS

The analysis is presented in three major parts. In the first part are developed the governing equations of transient heat transfer within and from the radiator system; these equations are the basis of the numerical simulation. The second part of the analysis is devoted to the computation of design parameters dictated by operational conditions, while third part covers the development of thermodynamic and transport properties of structural materials, coolant fluids, and the atmosphere.

A. System Description

Two radiator systems are considered in this analysis. The first system considers a flat radiator panel divided by regularly spaced coolant channels all having identical inlet coolant fluid properties. This system is treated rigorously. The second system considers a non-symmetrical radiator panel. The non-symmetrical conditions can be caused by a curvature in the radiator panel or by coolant channels that are parallel but not equally spaced or formed in the shape of a U. This system is treated in an approximate manner. The details of the non-symmetrical analysis are given in Section II D.

For the purposes of system simulation, the radiator system consists of four components:

(i) the fin

(ii) the coolant fluid

(iii) the coolant flow channel

(iv) the meteoroid protection layer

Two coordinate systems were introduced (see Figure 1), one for the fin and the other for the flow channel and the meteoroid protection layer. The rectangular Cartesian system (x,z) for the fin has its z-axis parallel to the tube axis, starting at the inlet plane, and its x-axis passing through the line of profile symmetry, with x = 0 designating the root of the fin. Cylindrical coordinates (r,z) are used for both the tube and the meteoroid protection layer, with the z-axis along the tube.

The radiator system is describable in terms of the following six dependent state variables:

(i) for the fin:

the fin temperature $T_f(t;x,z)$

(ii) for the coolant fluid:

the fluid temperature $T_c(t;z)$

the fluid pressure $p(t;z)$

the fluid velocity $w(t;z)$

(iii) for the fluid flow channel:

the tube wall temperature $T_w(t;r,z)$

(iv) for the meteoroid protection layer

the protection layer temperature $T_m(t;r,z)$

These six dependent variables must satisfy four equations of energy conservation, one for each component of the system, and further, the equations of mass conservation and of momentum balance for the fluid. These conservation equations take on the form of partial differential equations subject to initial and boundary conditions. Finally, the energy conservation equation for the fin involves the net radiant and convective power fluxes leaving the fin.

In the following Sections, II B.2 through II B.5 are discussed, in that order, the six principal governing equations associated with the four system components listed above, the subsidiary equations governing the radiative heat exchange and, lastly, the convective heat transfer between coolant fluid and tube wall and between the fin and the atmosphere during ascent and reentry.

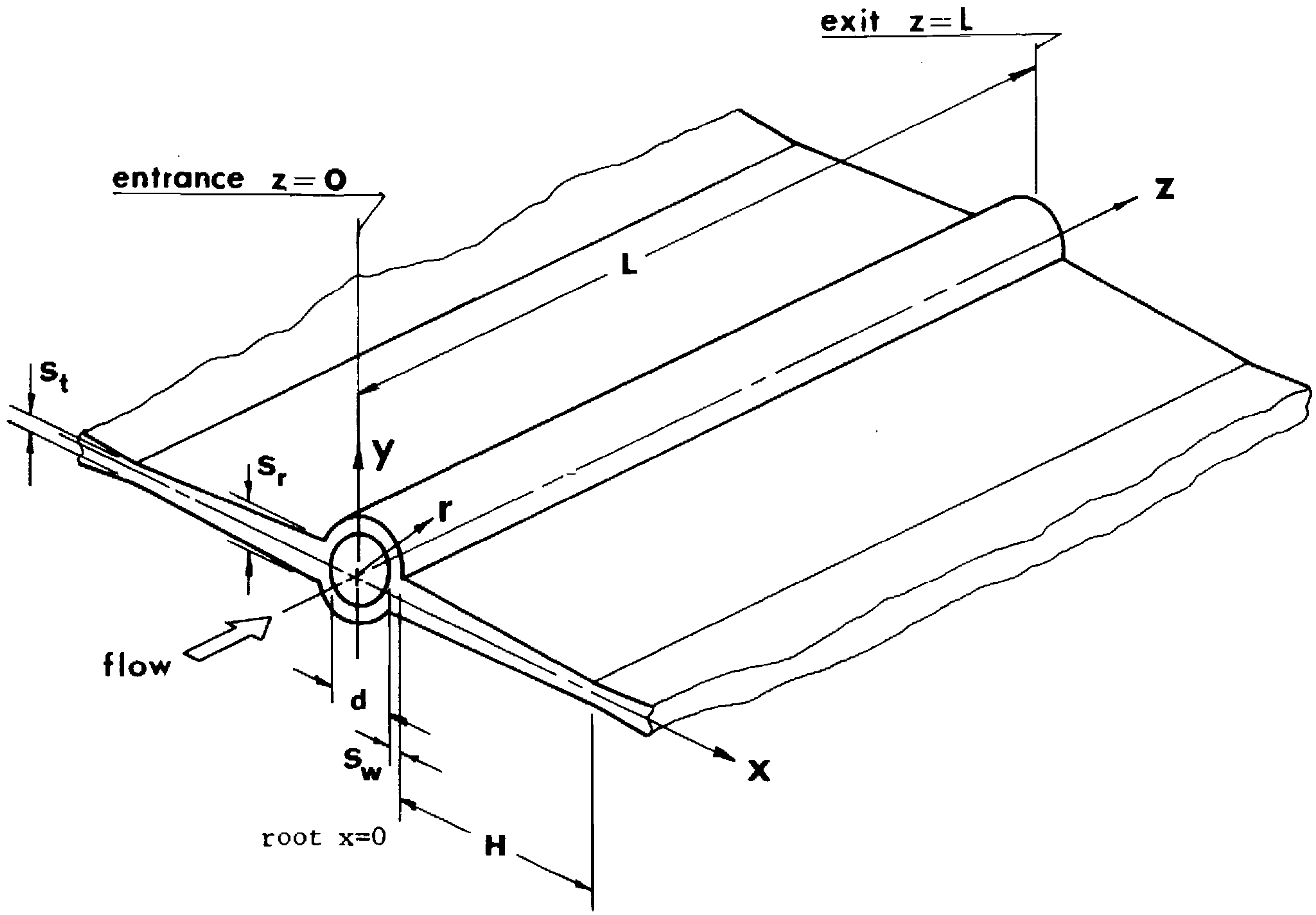

Figure 1 Fin Element and Coordinate System

B. HEAT TRANSFER

1. Introduction

The objective of the radiator simulation is to predict both the transient and the steady state heat transfer characteristics under predetermined operating conditions, stationary in the latter case and dynamic in the former. Both cases were treated as initial value problems, and the principal governing equations are partial differential equations which are linear in the time-derivatives of first order at most.

Under stationary boundary conditions steady state will be reached, regardless of initial conditions*, as all partial derivatives with respect to time vanish on account of dissipative effects within the system. For the computer simulation of steady state conditions this means that the process of advancing in time can be discontinued as soon as all variables y_i, $i = 1, 2, \ldots N$, have reached their expected asymptotic values $(y_i)_\infty$ with sufficient accuracy, that is when for some chosen ε_i

$$\delta_i = |y_i - (y_i)_\infty| \leq \varepsilon_i \tag{1.1}$$

has been reached. The expected asymptotic values $(y_i)_\infty$ can be estimated on the basis of the recognition that for large enough values of the time, $t > t_M$

$$y_i \rightarrow (y_i)_\infty \pm ae^{-bt} \tag{1.2}$$

with, $a > 0$, $b > 0$, to be determined; $t > t_M$. The evaluation δ_i during the numerical integration is covered in Chapter III.

*Subject to certain continuity requirements which are discussed in Chapter III.

2. The Fin

The objective of this section is to develop the energy equation for the fin. The derivation is based on the assumptions that the thermal conductivity and specific heat of the fin material are functions of temperature while the fin density is constant. The energy balance for the fin accounts for both radiative and convective fluxes from the fin surfaces. The development of a method to predict the net radiant flux from the fin surfaces can be found in Section II-6. The procedure used for the evaluation of the convective flux from the fin surface is outlined in Section II-7.

The energy balance on a differential volume of the fin can be expressed as

$$\frac{\partial}{\partial x}\left[k_f A_x \frac{\partial T_f}{\partial x}\right] dx + \frac{\partial}{\partial z}\left[k_f A_z \frac{\partial T_f}{\partial z}\right] dz + q''_{net,rad} A_s + q''_{aero} A_s = \rho_f V c_{pf} \frac{\partial T_f}{\partial t} \tag{2.1}$$

where T is the fin temperature and the coordinate system is shown in Fig. 1. The areas A_x and A_z represent the cross-sectional areas of the fin perpendicular to the heat flow in the x and z directions, and A_s represents the total non-adiabatic surface area of the fin element. The symbol V is the volume of the fin element. The properties of the fin material are represented by the symbols k_f, ρ_f and c_{pf} which stand for the thermal conductivity, density and specific heat, respectively. The terms $q''_{net,rad}$ and q''_{aero} appearing in Eq. 2.1 denote the radiative and convective heat gain from the surroundings to the fin surfaces.

The first two terms in Eq. 2.1 constitute the net conduction of energy into the fin element. The third and fourth terms on the left hand side of the equation stand for the net radiation and convection gain, respectively, from the surfaces of the fin element. The term of the right hand side of the equation represents the storage of internal energy within the fin element.

The appropriate areas and the volume to be substituted into Eq. 2.1 are

$$dA_x = 2[s_f - cx]\, dz \tag{2.2}$$

$$dA_z = 2[s_f - cx]\, dx \tag{2.3}$$

$$dA_s = dxdz/\left[c^2 + 1\right]^{1/2} \tag{2.4}$$

$$dV = 2[s_f - cx]\, dxdz \tag{2.5}$$

where s_f is the fin half thickness at its root and c is the negative slope of the fin side surfaces.

Substituting Eqs. 2.2 through 2.5 into Eq. 2.1 and simplifying the resulting equation yields

$$\rho_f\, c_{pf}\, \frac{\partial T_f}{\partial t} = k_f\left[\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial z^2}\right] + \frac{dk_f}{dT}\left[\left(\frac{\partial T_f}{\partial x}\right)^2 + \left(\frac{\partial T_f}{\partial z}\right)^2\right]$$

$$-\left(\frac{ck_f}{t-cx}\right)\frac{\partial T}{\partial x} + \frac{\sqrt{c^2+1}}{2(t-cx)}\left[q''_{net,rad} + q''_{aero}\right] \,. \tag{2.6}$$

The Normalization of Eq. 2.6 is achieved by defining nine dimensionless quantities:

Let

$$\xi = x/H \tag{2.7}$$

$$\zeta = z/L \tag{2.8}$$

represent the nondimensional fin coordinate perpendicular and parallel to the tube, respectively. Then

$$\tau = tw_o/L \tag{2.9}$$

is the dimensionless time. The symbol w_o stands for the velocity of the coolant fluid entering the tube.

The nondimensional fin temperature is defined as

$$\theta_f(\tau,\xi,\zeta) = \frac{T_f(\tau,\xi,\zeta)}{T_o} \tag{2.10}$$

where T_o is the temperature of the coolant fluid entering the tube.

The dimensionless conduction parameter N_{Nc} and the Fourier number are defined as

$$N_{Nc} = H\sigma T_o^{\,3}/k_f \tag{2.11}$$

$$N_{Fo} = \frac{\alpha_f L}{w_o H^2} = \frac{k_f \; L}{\rho_f c_{pf} w_o H^2} \tag{2.12}$$

and the nondimensional geometrical quantities are defined as

$$\bar{s}_f = s_f/H \tag{2.13}$$

$$B(\xi) = 2(\bar{s}_f - c\xi) \tag{2.14}$$

$$D = (c^2 + 1)^{1/2} \tag{2.15}$$

where c is the negative slope of the fin side surfaces. For a non-tapered fin c is zero.

Both the net radiative and convective flux terms appearing in Eq. 2.6 are normalized by dividing each term by σT_o^4, or

$$\tilde{q}_{net,rad} = \frac{q''_{net,rad}}{\sigma T_o^4} \tag{2.16}$$

$$\tilde{q}_{aero} = \frac{q''_{aero}}{\sigma T_o^4} \tag{2.17}$$

The energy equation, Eq. 2.6, may now be written in terms of the nondimensional quantities given in Eqs. 2.7 through 2.17. The resulting nondimensional equation is

$$\dot{\theta}_f = N_{Fo} \left\{ (\theta_f)_{\xi\xi} + \left(\frac{H}{L}\right)^2 (\theta_f)_{\zeta\zeta} + \frac{T_o}{k_f} \frac{dk_f}{dt} \left[(\theta_f)_{\xi}^{2} + \left(\frac{H}{L}\right)^2 (\theta_f)_{\zeta}^{2} \right] \right.$$
$$\left. - 2 \frac{c}{B} (\theta_f)_{\xi} + \frac{D}{B} N_{Nc} [\tilde{q}_{net,rad} + \tilde{q}_{net,conv}] \right\} \tag{2.18}$$

The dot superscript appearing in Eq. 2.18 denotes differentiation with respect to nondimensional time and the subscripts ξ and ζ represent partial differentiation with respect to the dimensionless coordinates indicated.

The normalized energy equation, Eq. 2.18, defines the rate of change of the dimensionless fin temperature θ_f.

<u>The Boundary Conditions</u> for Eq. 2.18 are taken as follows:

(i) The fin root is at the temperature of the outside of the tube.

(ii) The fin tip is insulated.

(iii) The portion of the fin in contact with the inlet manifold is at the outside temperature of the manifold.

(iv) The portion of the fin in contact with the exit manifold is at the temperature of the outlet manifold.

Written in mathematical terms these four boundary conditions are

$$\theta_f(\tau,0,\zeta) = \theta_w(\tau,\xi_o,\zeta) \tag{2.19}$$

$$\frac{\partial\theta_f}{\partial\xi}(\tau,1,\zeta) = 0 \tag{2.20}$$

$$\theta_f(\tau,\xi,0) = \theta_w(\tau,\xi_o,0) \tag{2.21}$$

$$\theta_f(\tau,\xi,1) = \theta_w(\tau,\xi_o,1) \tag{2.22}$$

Implied in Eqs. 2.21 and 22 is, firstly, that the fluid temperature in the manifolds be equal to the fluid temperature at the tube inlet (inlet manifold) and at the tube exit (exit manifold) and that it remain unaltered along the manifold and vary only in time; secondly, that the temperature drop through the manifold wall be equal to that through the tube wall. The latter assumption is well justified because the temperature drop is exceedingly small.

It may be noted in connection with the boundary conditions that the radiative interactions between manifold and fin as well as between manifold and tube are not taken into consideration at this time.

<u>The Initial Condition</u> for Eq. 2.18 may be any arbitrary relation representing a continuous temperature distribution over the fin, including the boundaries. The selection of the initial fin temperature distribution is left to the user.

3. The Coolant Fluid

The objective is to develop a unified treatment of all possible coolant fluids, that is gases, dielectric fluids and liquid metals. Three principal governing equations are sought which, together with the necessary thermodynamic and transport properties specified for each fluid of interest, define the fluid temperature T_c, the fluid pressure p (and thus the thermostatic state of the fluid) and the fluid velocity w, all as functions of time t and axial distance z.

The Continuity Equation for one dimensional flow through channels of constant cross-sections reads

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z} (\rho w) = 0 \tag{3.1}$$

where ρ represents the fluid density. Replacing the density through the thermal equation of state

$$p = p\ (\rho,\ T_c) \tag{3.2}$$

renders the continuity equation in terms of derivatives of the primary variables T_c, p and w:

$$\kappa \frac{\partial p}{\partial t} - \beta \frac{\partial Tc}{\partial t} = - \frac{\partial w}{\partial z} + w \left(\beta \frac{\partial Tc}{\partial z} - \kappa \frac{\partial p}{\partial z} \right) \tag{3.3}$$

where κ and β stand for the isothermal compressibility and the isobaric expansion coefficient, respectively

$$\kappa = \frac{1}{\rho} \left(\frac{\partial \rho}{\partial p} \right)_{Tc} \tag{3.4}$$

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T_c}\right)_p \tag{3.5}$$

The Momentum Equation

$$\rho\left(\frac{\partial w}{\partial t} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial p}{\partial z} - \frac{4f}{d}\rho\frac{w^2}{2} + \rho a_z \tag{3.6}$$

constitutes the balance between inertia forces on the left-hand side, pressure forces, wall friction and external field forces (gravity) in axial direction, on the right-hand side of Eq. 3.6. The Fanning friction factor f is a function of the Reynolds-number $N_{Re} = d\, w/\nu$, where d and ν stand for the tube diameter and the kinematic viscosity, respectively and subscript o designates the fluid inlet conditions. The following relations are used to compute the Fanning friction factor:

for $N_{Re} < 2300$ (laminar flow)

$$4f = \frac{64}{N_{Re}} \tag{3.7}$$

for $2300 \leq N_{Re} \leq 10^6$ (Ref. 1)

$$4f = 0.0054 + 0.396\, N_{Re}^{-0.3} \tag{3.8}$$

for $N_{Re} > 10^6$ (Ref. 2)

$$4f = 0.0032 + 0.221\, N_{Re}^{-0.237} \tag{3.9}$$

Equations 3.8 and 3.9 could be replaced by a single equation (Ref.3)

$$4f = [0.86859 \ \ell n \frac{N_{Re}}{1.964 \ \ell n \ N_{Re}} - 3.8215]^{-2} \tag{3.10}$$

which, however, requires more computational effort.

The Energy Equation. Let u, h, $\bar{h}_c$ and $T_w = T_w(t; r_i, k)$ represent, respectively the internal energy and the enthalpy of the fluid, the convective film coefficient and the tube wall temperature at the fluid-wall interface. For one-dimensional flow through channels of constant cross-section and with heating or cooling from the wall, conservation of energy requires that, with respect to a stationary reference frame

$$\frac{\partial}{\partial t} [\rho(u + \frac{w^2}{2})] + \frac{\partial}{\partial z} [\rho w \ (h + \frac{w^2}{2} - a_z z)] = \frac{4}{d} \bar{h}_c \ (T_w - T_c) + \frac{\partial}{\partial z} (k_c \frac{\partial T_c}{\partial z}) \tag{3.11}$$

The first term constitutes the storage of thermal and kinetic energies; the storage of potential energy, being negligibly small for expected accelerations, is ignored. The second term on the left-hand side stands for the convection of thermal, kinetic and potential energies as well as the power associated with the pressure. The right-hand side contains, firstly, the convective heat transfer from the channel wall to the fluid and, secondly, the axial heat conduction term which will later be shown to be negligibly small for all fluids. The factor 4/d in front of the convective heat transfer term results from the ratio of the channel circumference to the cross-sectional area, evaluated for a circular tube. The symbol k_c represents the thermal conductivity of the coolant.

Given a caloric equation of state

$$u = u(\rho, T_c) \tag{3.12}$$

or an equivalent expression for the specific heat, c_p, one can write, with the aid of Eqs. 3.2, 4 and 5

$$dh = c_p dT_c + \frac{1}{\rho} (1 - \beta T_c) \, dp \tag{3.13}$$

$$du = (c_p - \frac{p\beta}{\rho}) \, dT_c + \frac{1}{\rho} (\kappa p - \beta T) \, dp \tag{3.14}$$

and then recast Eq. 3.11 in terms of the derivatives of the principal variables T_c, p and w:

$$\rho \, c_p \frac{\partial T_c}{\partial t} - \beta T_c \frac{\partial p}{\partial t} + \rho w \frac{\partial w}{\partial t} = \frac{4}{d} \bar{h}_c \, (T_w - T_c) + \frac{\partial}{\partial z} (k_c \frac{\partial T_c}{\partial z}) - \rho w \, [c_p \frac{\partial T_c}{\partial z} + \frac{1}{\rho} (1 - \beta T) \frac{\partial p}{\partial z} + w \frac{\partial w}{\partial z} - a_z] \tag{3.15}$$

Thus, three governing equations, Eqs. 3.3, 3.6 and 3.15, have been established which define the three principal variables T_c, p and w, provided the initial and boundary conditions are properly specified and the convective film coefficient can be predicted. Since the normalization of these equations, followed by an order-of-magnitude comparison will indicate that the conductive term in Eq. 3.15 is negligible so as to simplify the boundary conditions, the discussion of the initial and boundary conditions is deferred until after the normalization.

The convective film coefficient is computed from the following relationships between the Nusselt number $N_{Nu} = \bar{h}_c d/k_c$, the Reynolds number

N_{Re} and the Prandtl number $N_{Pr} = \mu\, c_p/k_c$ where μ represents the dynamic viscosity:

For $N_{Pr} < 0.1$ (liquid metals)

$$N_{Nu} = 6.5 + 0.025\ (N_{Re}\ N_{Pr})^{0.8} \tag{3.16}$$

which produces Nusselt numbers between those appropriate for uniform heat flux (Martinelli) and for uniform wall temperature (Seban and Shimazaki) (Ref. 4).

For $N_{Pr} > 0.1$ and

for $N_{Re} < 2300$ (laminar flow, Ref. 5)

$$N_{Nu} = 3.65 + \frac{0.0668\ (N_{Re} N_{Pr} \delta)}{1 + 0.045\ (N_{Re} N_{Pr} \delta)} \tag{3.17}$$

for $N_{Re} \geq 2300$ (turbulent flow, Ref. 5)

$$N_{Nu} = 0.116\ (N_{Re}^{\ 0.667} - 125)\ N_{Pr}^{\ 0.333}\ (1 + \delta) \tag{3.18}$$

where $\delta = d/L$ stands for the tube diameter-over-length ratio.

<u>The Normalization</u> of Eqs. 3.3, 6 and 15 is carried out for the purpose of scaling and performing an order-of-magnitude comparison. The computational effort is also reduced in the process.

Let

$$\zeta = z/L \tag{3.19}$$

$$\tau = t w_o/L \tag{3.20}$$

represent the nondimensional axial distance and the nondimensional time, respectively, and let the dimensionless state variables be defined as

$$\theta_c\ (\tau,\zeta) = \frac{T_c(t,z)}{T_o} \tag{3.21}$$

$$\pi\ (\tau,\zeta\ ) = \frac{p\ (t,z)}{p_o} \tag{3.22}$$

$$\omega\ (\tau,\zeta\ ) = \frac{w\ (t,z)}{w_o} \tag{3.23}$$

and to represent the nondimensional temperature, pressure and velocity of the fluid, that is, the principal dependent fluid flow variables. The subscript "o" designates the constant reference state of the fluid at the tube entrance. Introduce next the nondimensional density

$$\nu(\tau,\ \zeta) = \frac{\rho(t,z)}{\rho_o}\ , \tag{3.24}$$

the nondimensional radial distance from the channel axis

$$\eta = \frac{2r}{d}, \tag{3.25}$$

and the nondimensional tube wall temperature

$$\theta_w\ (\tau;\eta,\zeta) = \frac{T_w(t;r,z)}{T_o} \tag{3.26}$$

Notice, that all dependent variables lie between zero and unity, except ν and ω whose product $(\nu\omega)$ remains essentially equal to unity with neither ν nor ω departing far from unity. The reference temperature T_o is, under normal operating conditions, the highest temperature in the system.

Furthermore, consider the following ϕ-values to vary along the channel axis:

$$\phi_\beta = T_o \beta \tag{3.27}$$

$$\phi_\kappa = p_o \kappa \tag{3.28}$$

$$\phi_{cp} = \frac{c_p}{c_p\ (\rho_o,\ T_o)} = \frac{c_p}{c_{p,o}} \tag{3.29}$$

$$\phi_k = \frac{k}{k\ (\rho_o,\ T_o)} = \frac{k}{k_o} \tag{3.30}$$

and finally, the following constant F-parameters:

$$F_p = \frac{p_o}{\rho_o w_o^{\ 2}} \tag{3.31}$$

$$F_f = 4f\ \frac{L}{d} = \frac{4f}{\delta} \tag{3.32}$$

$$F_z = \frac{p_o}{\rho_o c_{p,o} T_o} \tag{3.33}$$

$$F_M = F_z / F_p = \frac{w_o^{\ 2}}{C_{po} T_o} \tag{3.34}$$

Let the dot above a variable designate partial differential with respect to the nondimensional time τ and the subscript ζ partial differentiation with respect to the dimensionless axial coordinate ζ. Then the principal conservation equations, Eqs. 3.3, 3.6 and 3.15 read, respectively and in nondimensional form:

$$\phi_\beta \left[\dot{\theta}_c + \omega(\theta_c)_\zeta\right] = \omega_\zeta + \phi_\kappa(\dot{\pi} + \omega\pi_\zeta) \tag{3.35}$$

$$\dot{\omega} + \omega\,\omega_\zeta = -\frac{F_p}{\nu}\,\pi_\zeta - F_f\,\frac{\omega^2}{2} \tag{3.36}$$

$$\dot{\theta}_c - F_z\frac{\phi_\beta}{\phi_{cp}}\,\frac{\theta_c}{\nu} + F_M\,\frac{1}{\phi_{cp}}\,\omega\omega_\zeta = \delta\frac{4N_{Nu}}{N_{Re}N_{Pr}}\cdot\frac{1}{\nu\phi_{cp}}(\theta_\omega - \theta_c) + \frac{\delta^2}{4N_{Nu}}$$

$$\times\left[\phi_\kappa(\theta_c)_\zeta\right]_\zeta - \omega(\theta_c)_\zeta +$$

$$F_z\,\frac{1-\theta_c\phi_\beta}{\phi_{cp}}\cdot\frac{1}{\nu}\pi_\zeta + F_M\,\frac{1}{\phi_{cp}}\,\omega\,\omega_\zeta \tag{3.37}$$

These are the three equations which define the three time rates of change, $\dot{\theta}_c$, $\dot{\pi}$ and $\dot{\omega}$. It can be seen from Eq. 3.37 that the axial conduction is always small, of an order less than δ^2 (since $N_{Nu} > 3$), when compared with the convective term, unless the fluid should reach the wall temperature within the very first small fraction of the tube length. Axial conduction is hence ignored as $\delta^2 \approx 10^{-6}$, and the order of differentiation of Eq. 3.37 is reduced to one.

$$\dot{\theta}_c - F_z \frac{\phi_\beta}{\phi_{cp}} \frac{\theta_c}{\nu} \dot{\pi} + F_M \frac{1}{\phi_{cp}} \omega\dot{\omega} = \frac{4N_{Nu}}{\delta N_{Rc} N_{Pr}} \frac{\theta_w - \theta_c}{\nu \phi_{cp}} - \omega\left\{(\theta_c)_\zeta + F_z \times \right.$$

$$\left. \frac{1 - \theta_c \phi_\beta}{\nu\phi_{cp}} \pi_\zeta + \frac{F_M}{\phi_{cp}} \omega\omega_\zeta \right\} \quad (3.38)$$

<u>The Boundary Conditions</u> to be imposed on Eqs. 3.35, 3.36 and 3.38 are chosen, at the channel entrance, to be

(i) mass flow rate $\dot{m}$, prescribed as a function of time

(ii) constant inlet pressure P_o.

(iii) continuous transition, of the inlet fluid temperature, from an initial temperature $\theta = \theta_i$ to the constant operational temperature $\theta(t,0) = 1$, or an arbitrarily prescribed inlet fluid temperature that is a continuous function of time

These boundary conditions accommodate the calculation of the steady state conditions as well as of the most likely start-up operation toward stationary operating conditions. Notice that there are no step changes implied in any of the dependent variables which is essential for the numerical integration. Writing these boundary conditions more specifically, one gets at $\zeta = 0$

$$\theta\ (\tau,\ 0) = 1 - (1 - \theta_i)\ e^{-7\tau} \quad (3.39)$$

$$\pi\ (\tau,\ 0) = 1 \quad (3.40)$$

$$\omega\ (\tau,\ 0) = \frac{1}{\nu(\pi,\ \theta)} \quad (3.41)$$

Here, the time constant was chosen arbitrarily so as to have the fluid reach, within 0.1%, its steady inlet temperature at the inlet during the time interval that is takes a fluid particle to pass through the channel. Equation 3.41 is given through the thermal equation of state, Eq. 3.2.

The Initial Conditions appropriate to the system of Eqs. 3.35, 3.36 and 3.38 are derived from the requirement that the flow should initially be at steady state with the fluid inlet temperature equal to the uniform channel wall temperature. Setting the time derivatives equal to zero in Eqs. 3.35, 3.36 and 3.38 results in a system of three ordinary differential equations which are linear in $d\pi/d\zeta$, $d\theta_c/d\zeta$ and $d\omega/d\zeta$:

$$F_p \frac{d\pi}{d\zeta} + \frac{d\omega}{d\zeta} = - F_f \nu \frac{\omega^2}{2} \tag{3.42}$$

$$F_z \frac{\phi_\beta}{\nu} \frac{d\pi}{d\zeta} + \frac{d\theta_c}{d\zeta} + \frac{F_M}{\phi_{cp}} \omega \frac{d\omega}{d\zeta} = \frac{4N_{Nu}}{\delta N_{Rc} N_{Pr}} (\theta_w - \theta_c) \tag{3.43}$$

$$\phi_\kappa \frac{d\pi}{d\zeta} - \phi_\beta \frac{d\theta_c}{d\zeta} + \frac{1}{\omega} \frac{d\omega}{d\zeta} = 0 \tag{3.44}$$

These equations can be solved subject to the boundary conditions at $\zeta = 0$

$$\left.\begin{aligned} \pi &= 1 \\ \theta_c &= \theta_i \\ \omega &= \frac{1}{\nu(\pi, \theta_c)} \end{aligned}\right\} \tag{3.45}$$

provided the function $\theta_w = \theta_w(0; 1,\zeta)$ prescribing the initial channel wall temperature is specified. For the present analysis θ_w was set equal to θ_i. Equations 3.42 through 3.45 define the initial flow field.

Quasi-Steady Flow. It may be recognized that the momentum transport takes place at a much smaller time scale than the transport of thermal energy in that the pressure and the velocity fields adjust virtually instantaneously to a change in flow inlet conditions while the response of the temperature field to a change in channel wall temperature takes considerably longer, the reason being that the pressure perturbations propagate along the channel with the speed of sound. Unless one is specifically interested in the motion of sound waves one may consider the dynamics of the flow field, that is the pressure and velocity distributions, as part of the boundary conditions and imposed instantly and adiabatically by the flow inlet conditions.

The fluid temperature remains stationary during the dynamic adjustment and the time rate of change of both pressure and temperature remain small since ordinarily the pressure gradient remains balanced by the wall shear (and by the convective acceleration in the case of a gaseous coolant medium). Consequently, Eqs. 3.42 and 3.44 may serve to establish the pressure and velocity fields at all times, subject to boundary conditions given by Eqs. 3.40 and 3.41 while the temperature field remains defined by Eqs. 3.35, 36, 38 and the initial conditions discussed above. Particularly, solving Eqs. 3.35, 36 and 38 for $\dot{\theta}_c$ gives the differential equation which governs the temperature field:

$$\dot{\theta}_c = \frac{1}{1 - \dfrac{F_z}{\phi_{cp}} \dfrac{\phi_\beta^2}{\phi_\kappa} \dfrac{\theta}{\nu}} \left\{ \frac{4N_{Nu}}{\delta N_{Re} N_{Pr}} (\theta_w - \theta_c) + F_z \frac{\phi_\beta}{\phi_{cp}\phi_\kappa} \times \left[\phi_\beta \, \omega(\theta_c)_\zeta - \frac{\theta_c}{\nu} \omega_\zeta \right] - \omega \left[(\theta_c)_\zeta + F_M F_f \frac{1}{\phi_{cp}} \frac{\omega^2}{2} \right] \right\} \tag{3.46}$$

This completes the discussion of the development of the governing differential equations for the coolant fluid. All equations are solved numerically as discussed in Chapter III. The thermodynamic properties c_p, β, and κ are derived from the thermal equation of state, Eq. 3.2 and from the zero-pressure specific heat or other available properties. All thermodynamic functions as well as the transport properties κ and μ are considered, in general, as functions of two state variables, that is, of ρ and T or of p and T, as discussed in Section E of Chapter II.

4. The Flow Channel

The flow channel is treated as a circular tube with inner radius $r_i = d/2$ and outer radius $r_o = r_i + s_t$. The tube wall temperature $T_w(t;r,z)$ is defined through the familiar equation of energy conservation, written for the case of circular symmetry:

$$\frac{\partial T_w}{\partial t} = \alpha_w \left[\frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial T_w}{\partial r}\right) + \frac{\partial^2 T_w}{\partial z^2} \right] + \frac{1}{(\rho c)_w} \frac{dk_w}{dT} \left[\left(\frac{\partial T_w}{\partial r}\right)^2 + \left(\frac{\partial T_w}{\partial z}\right)^2\right], \tag{4.1}$$

where α_w represents the thermal diffusivity of the wall material and $(\rho c)_w$ its volumetric heat capacity. The boundary conditions are

at $r = r_i$

$$\bar{h}_c \,(T_w - T_c) = k_w \frac{\partial T_w}{\partial r} \tag{4.2}$$

at $r = r_o$

$$k_w \frac{\partial T_w}{\partial r} - \psi k_f \frac{\partial T_f}{\partial x} - (2\pi - \psi)\, k_m \frac{\partial T_m}{\partial r} = 0 \tag{4.3}$$

Here

- $\bar{h}_c$ is the convective film coefficient,
- T_c the fluid temperature,
- k the thermal conductivity,
- ψ the portion of outer tube circumference in contact with fins, expressed in radians,

and the subscripts w, f and m designate, respectively, tube wall, fin and meteoroid protection layer. Equations 4.2 and 3 constitute the continuity of the heat flux at the fluid-wall interface and at the wall-fin and wall-protection layer interfaces. Circumferential temperature variations are ignored.

After introducing

$$\eta = \frac{r}{r_i}, \quad \zeta = \frac{x}{H}; \quad \tau = \frac{tw_o}{L}; \quad \theta_w = \frac{T_w}{T_o},$$

$$\phi_c = \frac{k_c}{k_w}, \quad \phi_f = \frac{k_f}{k_w} \frac{r_i}{H},$$

$$\phi_m = \frac{k_m}{k_w} \qquad N_{Bi} = \frac{\bar{h}_c d}{k_w}, \tag{4.4}$$

$$\delta = \frac{d}{L}, \quad \phi_{\kappa w} = \frac{T_o}{k_w} \frac{dk_w}{dT}, \quad \phi_{Fo,w} = \frac{\alpha_w L}{w_o r_i^2}$$

with H representing the fin height, that is, the distance between the fin root and fin tip, one may recast Eqs. 4.1, 2 and 3 to read

$$\dot{\theta}_w = \phi_{Fo,w} \left\{ \frac{1}{\eta} \frac{\partial}{\partial \eta} \left(\eta \frac{\partial \theta_w}{\partial \eta} \right) + \left(\frac{\delta}{2}\right)^2 \frac{\partial^2 \theta_w}{\partial \zeta^2} \right.$$

$$\left. + \phi_{\kappa w} \left[\left(\frac{\partial \theta_w}{\partial \eta}\right)^2 + \left(\frac{\delta}{2}\right)^2 \left(\frac{\partial \theta_w}{\partial \zeta}\right)^2 \right] \right\} \tag{4.5}$$

at $\eta = 1$

$$\frac{1}{2} N_{Bi} (\theta_w - \theta_c) = \frac{\partial \theta_w}{\partial \eta} \tag{4.6}$$

at $\eta = \eta_o$

$$\frac{\partial\theta_w}{\partial\eta} - \psi\phi_f \frac{\partial\theta_f}{\partial\xi} - (2\pi - \psi)\,\phi_m \frac{\partial\theta_m}{\partial\eta} = 0 \tag{4.7}$$

The superscript dot represents partial differentiation with respect to nondimensional time τ. As before in the treatment of the coolant fluid one recognizes that, with $\delta^2 \approx 10^{-6}$, axial conduction remains insignificant. Thus, Eq. 4.5 takes on this final form

$$\dot{\theta}_w = \phi_{Fo,w} \left\{ \frac{1}{\eta} \frac{\partial}{\partial\eta} \left(\eta \frac{\partial\theta_w}{\partial\eta}\right) + \phi_{kw} \left(\frac{\partial\theta_w}{\partial\eta}\right)^2 \right\} \tag{4.8}$$

Equations 4.6, 7 and 8 define the tube wall temperature, provided Eqs. 4.6 and 7 hold at some initial time and the initial temperature $\theta_w(0;\eta,\zeta)$ is prescribed as a sufficiently smooth function of η and ζ.

Low Biot Number. When one compares possible heat fluxes at the fluid-wall interface with the possible radiant fluxes from the outer surface of the meteoroid protection layer covering the tube, one concludes that the maximum fluxes occur at the inner tube wall and that the Biot number N_{Bi} in Eq. 4.6 is the largest ratio to be expected of external to internal thermal conductances. Thus, if N_{Bi} is small, say less than 0.05 (Ref. 6), then the temperature variation inside the tube wall is too small for experimental detection and a computation of the detailed temperature distribution on the basis of Eq. 4.8 cannot be justified as the associated computational effort is considerable.

In cases where the equivalent Biot number, representing the total thermal resistance within the channel wall and the protection layer, is small, the tube, the protection layer and a representative portion of the fin root are combined into a single control volume as depicted in Fig. 2. The equivalent Biot number $\bar{N}_{Bi}$ and the chosen limit are

$$\bar{N}_{Bi} = N_{Nu} \frac{k_c}{d} \left(\frac{s_w}{k_w} + \frac{s_m}{k_m}\right) < 0.05 \tag{4.9}$$

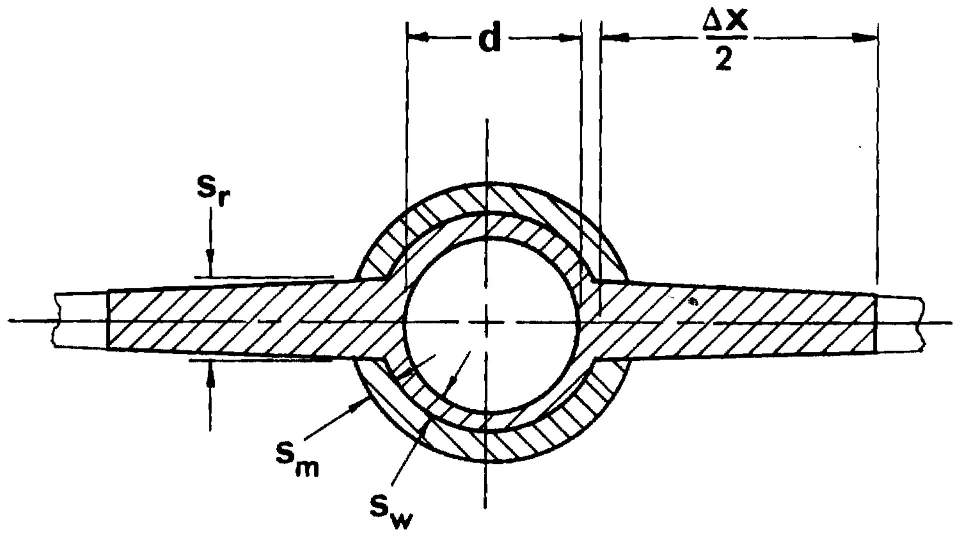

Figure 2. Control Volume for Low-Biot Number Cases

where s_w and s_m stand for, respectively, the tube wall and the protection layer thicknesses. The combined volumetric heat capacity per unit of axial distance for the control volume consists of three parts, the first one for the tube wall, the second for the protection layer and the third for the first half fin element:

$$\pi d\ (\rho cs)_w \left\{ (1 + \frac{s_w}{d}) + (1 + 2\frac{s_w}{d} + \frac{s_m}{d}) \frac{(\rho cs)_m}{(\rho cs)_w} + \frac{\Delta x}{\pi d}\ \frac{s_r}{s_w} \times \right.$$

$$\left. [1 - \frac{\Delta\xi}{4}(1 - \frac{s_t}{s_r})]\ \frac{(\rho c)_f}{(\rho c)_w} \right\} = \lambda_1\ \pi d\ (\rho cs)_w \tag{4.10}$$

where the subscripts w, m, f, r and t designate, respectively, parameters of the tube wall, the meteoroid protection layer, the fin, the fin root and the fin tip and where

- d is the tube diameter,
- ρ the density,
- s the thickness,
- Δx the node spacing on the fin, and
- $\Delta\xi$ = $\Delta x/H$, the nondimensional node spacing

Heat enters the control volume, per units of time and axial distance, by convection from the fluid

$$\pi d\ \bar{h}_c\ (T_w - T_c),$$

and by convection and/or radiation from outside

$$(2\pi - \psi)\ (\frac{d}{2} + s_w + s_m)\ q''_m + \Delta x\ (q''_1 + q''_2)_f$$

where the subscripts 1 and 2 designate upper and lower fin sides, respectively, and where q" represents the sum of the convective and of the net radiant fluxes entering the outer surfaces. In the case of q''_m, the average over upper and lower portions of the outer circumference is to be taken.

Heat leaves the control volume through the fin by conduction, again per units of time and axial distance

$$2(s\,\frac{\partial T}{\partial x})_f$$

evaluated at $x = \Delta x/2$.

Combining the last four expressions into the energy balance leads to this expression

$$\lambda_1\, \pi d\, (\rho cs)_w \frac{\partial T_w}{\partial t} = \pi d\, \bar{h}_c\, (T_w - T_c) + \pi d\, \lambda_2\, q''_m + \Delta x\, (q''_1 + q''_2)_f + 2\, (s\,\frac{dT_f}{dx})\Big|_{\frac{\Delta x}{2}} \tag{4.11}$$

where λ_1 is defined by Eq. 4.10 and

$$\lambda_2 = (2 - \frac{\psi}{\pi})\ (\frac{1}{2} + \frac{s_w + s_m}{d}) \tag{4.12}$$

Equation 4.11 replaces Eqs. 4.6, 7 and 8 as well as Eqs. 5.3, and 5 governing the temperature distribution in the meteroid protection layer and, lastly, Eq. 2.19 which constitutes one of the boundary conditions for the differential equation governing the fin temperature distribution. The only condition under which all the above equations may be replaced by the single equation, Eq. 4.11, is given by Eq. 4.9. Finally, it may be noted that Eq. 4.11 could also be normalized but since no new dimensionless groups result from such normalization it is omitted here.

5. The Meteoroid Protection Layer

The differential equation governing the temperature distribution within the meteoroid protection layer which covers the flow channel, is identical to that for the channel wall, Eq. 4.8, except for the two dimensionless parameters, the Fourier coefficient ϕ_{Fo} and the conductivity temperature coefficient ϕ_k which now must be evaluated for the protection layer material:

$$\phi_{Fo,m} = \frac{\alpha_m}{\alpha_w} \phi_{Fo,w} \tag{5.1}$$

$$\phi_{k,m} = \frac{T_o}{k_m} \frac{dk_m}{dT} \tag{5.2}$$

After ignoring the axial conduction for the reasons stated in Section 4 one obtains as the nondimensional energy conservation equation

$$\dot{\theta}_m = \phi_{Fo,m} \left\{ \frac{1}{\eta} \frac{\partial}{\partial \eta} \left(\eta \frac{\partial \theta_m}{\partial \eta} \right) + \phi_{k,m} \left(\frac{\partial \theta_m}{\partial \eta} \right)^2 \right\} \tag{5.3}$$

Two boundary conditions are required, one of which is given by Eq. 4.7 while the other one is dictated by the heat flux continuity at the outer boundary:

at $r = r_e$

$$k_m \frac{\partial T_m}{\partial r} = q''_m \tag{5.4}$$

where q" is defined as the net flux <u>entering</u> both by radiation and/or aerodynamic heating. Equation 5.4 reads in nondimensional form at $\eta = \eta_e$

$$\frac{\partial \theta_m}{\partial \eta} = \phi_{Nc} (\tilde{q}_{net,rad} + \tilde{q}_{aero}) \tag{5.5}$$

with ϕ_{Nc} representing a local conductance parameter

$$\phi_{Nc} = \frac{\sigma d T_o^3}{2k_m} \tag{5.6}$$

and

$$\tilde{q}_{net,rad} = \frac{q''_{net,rad}}{\sigma T_o^4} \tag{5.7}$$

$$\tilde{q}_{aero} = \frac{q''_{aero}}{\sigma T_o^4} \tag{5.8}$$

Here, σ represents the Stefan-Boltzmann constant, and $q''_{net,rad}$ and q''_{aero} the net radiant incident heat flux and the convective heat flux, respectively.

If the initial temperature distribution is given, and if Eqs. 4.7 and 5.5 hold initially, then the protection layer temperature θ_m is completely defined as a function of time and location by Eqs. 5.3, 5 and 4.7, provided the incident radiation and the aerodynamic heating are prescribed as functions of time. The prediction of these incident heat fluxes is discussed in Section 6 and 7 of this Chapter.

In the case of low Biot numbers at the coolant fluid-tube wall interface the meteoroid protection layer is lumped together with the tube wall as discussed in Section 4 of Chapter II.

6. Radiation

The objective of this section is to develop a procedure to predict the net radiant heat flux incident on fin and tube surfaces which are exposed to any combination so solar, albedo and planetary irradiation. Included into the assessment of radiative transfer is the radiative energy exchange between fin panel and flow channel or its protective coating as well as the effect of structural panels in the vicinity of the fin system; however, not included is any possible gas radiation as could conceivably be encountered during reentry.

In seeking the proper mathematical model it is recognized, firstly, that the prevailing thermal radiant energy lies in either the visible (solar irradiation) or the infrared portion of the spectrum, and, secondly, that the fin system is coated, for the purpose of optical optimization, with a dielectric paint. Consequently, spectrally dependent optical properties must be dealt with, but, for the latter reason, the transfer matrix of radiative exchange can be expected to remain temperature insensitive over some range of operational conditions, a fact which is very much appreciated from the computational view point.

For the analysis, the fin surface A_f, the outer surface on the flow channel A_n, and the structural surface(s) A_n, are all considered as parts of an enclosure C which is completed by a set of arbitrarily concave, non-reflecting imaginary surfaces A_e which connect A_m, A_f and A_n and along which is specified the emerging net radiant heat flux representing solar, albedo and planetary irradiation. The sum $A_m + A_f + A_n + A_e$ is the inner surface A_c of the enclosure.

Three steps are necessary for the prediction of the incident net radiant heat flux $q''_{net,rad}$. Firstly, the elemental exchange areas*

$$\frac{\partial^2 \overline{s_i s_j}}{\partial A_i \partial A_j} = \frac{\cos\phi_i \cos\phi_j}{\pi r^2} \tag{6.1}$$

*For terminology and notations consult Ref. 7, Chapter 2.

need to be computed on the basis of the geometric relation between fin panels and flow channels. Here, the symbol r designates the distance between two area elements dA_i and dA_j which are visible from each other, and ϕ_i and ϕ_j represent the respective angles between r and the surface normals on dA_i and dA_j. The next step is to compute, from its definition, the radiosity or leaving radiant flux density, W_j:

$$W_j = \int_o^{\infty} W_{j,\lambda} \, d\lambda = \int_o^{\infty} \varepsilon_{j,\lambda} E_{j,\lambda} \, d\lambda + \int_{A_c} \frac{\partial^2 \, \overline{s_i s_j}}{\partial A_i \partial A_j} \int_o^{\infty} (1 - \varepsilon_{j,\lambda}) W_{i,\lambda} \, d\lambda \quad dA_i \tag{6.2}$$

where $W_{j,\lambda}$, $E_{j,\lambda}$ and $\varepsilon_{j,\lambda}$ stand for the monochromatic radiosity, the monochromatic black body emissive power

$$E_{j,\lambda} = \frac{2 \, hc^2 n^2}{\lambda^5} \; \frac{1}{e^{(hc)/(k\lambda T_j)} - 1} \tag{6.3}$$

and the monochromatic hemispherical emittance, respectively; the subscripts i and j designate two discrete points on A_c, and λ represents the wavelength. The Eq. 6.3 constitutes Planck's law of monochromatic emissive power intensity; h, c and k stand for, respectively, Planck's constant, the speed of light in vacuo and the Boltzmann constant. The third and last step is to calculate, on the basis of local energy balance, the net incident heat flux

$$(q''_{net,rad})_j = \int_o^{\infty} q''_{j,\lambda} \, d\lambda = \int_{A_c} (W_i - W_j) \; \frac{\partial^2 \, \overline{s_i s_j}}{\partial A_i \partial A_j} \; dA_i \tag{6.4}$$

It should be obvious that Eqs. 6.1, 2 and 4 contain all the necessary fundamental principles but their evaluation will introduce a number of simplifications and modifications, each selected for the particular system of interest. Specifically, Eq. 6.4 will have to supplement Eq. 6.2 for portions of A_c where the heat flux is specified. More importantly, however, there is a choice to be made in view of the computational process regarding particularly Eq. 6.2. One may either solve the monochromatic version of Eq. 6.2 n times for the n significant spectral intervals encountered and thus face the ultimate task of solving n x N simultaneous linear algebraic equations when N discrete points on A_c need to be considered (possibly at several time steps during the calculation process) and then integrate the resulting total interchange areas over the spectrum (see Ch. 5.6 of Ref. 7). Or, one may force the non-gray surface analysis into a gray surface analysis by placing the burden of complexity on the evaluation of appropriate optical properties. Both techniques afford any desirable accuracy of allowing for the spectral differences in surface properties, limited only by available calculation time; but the latter technique was chosen because, as a result of this choice, the complexity remains at peripheral parts of the computer code which are more accessible for later modifications toward greater sophistication, also the complexity may turn out, in almost all cases, to reduce partly to simple hand calculations.

After introducing

$$\varepsilon_i = \frac{\int_o^\infty \varepsilon_{i,\lambda} E_{i,\lambda}\, d\lambda}{\int_o^\infty E_{i,\lambda}\, d\lambda} = \frac{1}{E_i} \int_o^\infty \varepsilon_{i,\lambda} E_{i,\lambda}\, d\lambda \tag{6.5}$$

$$\alpha_{ij} = \frac{\int_o^\infty \varepsilon_{i,\lambda} W_{j,\lambda}\, d\lambda}{\int_o^\infty W_{j,\lambda}\, d\lambda} \tag{6.6}$$

Equation 6.2 simplifies to

$$W_j = \epsilon_j E_j + \int_{A_c} \frac{\partial^2 \overline{s_i s_j}}{\partial A_i \partial A_j} (1 - \alpha_{ij}) W_i \, dA_i \tag{6.7}$$

which reduces to the gray-surface radiosity equation whenever Eq. 6.6 reduces to $\alpha_{ij} = \epsilon_i$. The difficulty now lies in evaluating Eq. 6.6 even though the radiosity $W_{j,\lambda}$ is as yet unknown.

By successively substituting the right-hand side of Eq. 6.2, in its monochromatic form, for $W_{i,\lambda}$ on the right-hand side of that equation, one obtains first (Ref. 8)

$$W_{j,\lambda} = \epsilon_{j,\lambda} E_{j,\lambda} + (1 - \epsilon_{j,\lambda}) \Bigg\{ \int_{A_c} \frac{\partial^2 \overline{s_i s_j}}{\partial A_i \partial A_j} \Bigg[\epsilon_{i,\lambda} E_{i,\lambda} + (1 - \epsilon_{i,\lambda}) \int_{A_c} \Big(\frac{\partial^2 \overline{s_i s_m}}{\partial A_i \partial A_m} \epsilon_{m,\lambda} E_{m,\lambda} + \ldots \Big) dA_m \Bigg] dA_i \tag{6.8}$$

and subsequently α_{ij} as the quotient of two infinite series. Since the enclosure radiation is dominated by the fin-sun and fin-sky interaction and since Eq. 6.8 contributes significantly only to the fin-flow channel interaction, the infinite series in Eq. 6.8 may be terminated after two terms (two reflections; the resulting error is less than the uncertainty in ϵ_λ), and Eq. 6.6 becomes:

$$\alpha_{ij} = \frac{X_{ij} E_j + \int_{A_c} \frac{\partial^2 \overline{s_j s_k}}{\partial A_j \, \partial A_k} E_k (X_{ik} - X_{ijk}) \, dA_k}{\epsilon_j E_j + \int_{A_c} \frac{\partial^2 \overline{s_j s_k}}{A_i \, A_k} E_k (\epsilon_k - X_{jk}) \, dA_k} \tag{6.9}$$

where

$$X_{ij} = \int_{o}^{\infty} E_{j,\lambda}\, \varepsilon_{j,\lambda}\, \varepsilon_{i,\lambda}\, d\lambda \Big/ E_j \tag{6.10}$$

$$X_{ijk} = \int_{o}^{\infty} E_{k,\lambda}\, \varepsilon_{k,\lambda}\, \varepsilon_{j,\lambda}\, \varepsilon_{i,\lambda}\, d\lambda \Big/ E_k \tag{6.11}$$

In cases where the net radiant flux is specified over portions of A, the emissive power E is to be replaced by the net radiant flux q" in Eqs. 6.9, 10 and 12, which results in one additional term each in the numerator and the denominator of Eq. 6.9.

In summary, the incident net radiant heat flux for the diffuse, non-gray enclosure is calculated on the basis of an approximate gray-surface analysis in accordance with Eqs. 6.4, 7 and 9 through 11. The spectral differences of the surfaces are accounted for in Eqs. 9 through 11. The remainder of this section is devoted to the solution of the radiosity equation, Eq. 6.7.

Recalling that A_c is the sum $A_m + A_n + A_f + A_e$ of the outer channel surface A_m, the possibly present, nearby structural surfaces A_n, the fin surface A_f, and the remainder of the enclosure A_e, one recognizes that the integrals over A_c in Eqs. 6.4, 7 and 9 need to be evaluated twice for each of the four parts, namely once with j = 1 representing the fin area and then with j = 2 for the exposed channel area. Since the incident solar, albedo and planetary radiant flux intensities are uniform over the fin area and averaged over the circumference of the channel area

$$\int_{A_e} \frac{\partial^2 \overline{s_i s_1}}{\partial A_i \partial A_1} (1 - \alpha_{i1})\, W_i dA_i = (1 - \alpha_{e1})\, q''_{e1} \tag{6.12}$$

$$\int_{A_e} \frac{\partial^2 \overline{s_i s_2}}{\partial A_i \partial A_2} (1 - \alpha_{i2}) W_i dA_i = (1 - \alpha_{e2}) q''_{e2} \tag{6.13}$$

where q" designates incident solar, albedo and planetary heat fluxes, appropriately averaged over a chosen area element. Should any structural surfaces obstruct the incident radiant fluxes ($A_n \neq 0$) then the right-hand sides of Eqs. 6.12 and 13 would have to be modified and reduced in the shaded portions of A_1 and A_2; and, if there are m such surfaces,

$$\int_{A_n} \frac{\partial^2 \overline{s_i s_j}}{\partial A_i \partial A_j} (1 - \alpha_{ij}) W_i dA_i = \sum_{k=1}^{m} \frac{\partial \overline{s_k s_j}}{\partial A_j} (1 - \alpha_{kj}) W_k , \tag{6.14}$$

$$j = 1, 2, \ldots m + 2.$$

Obviously, the radiosity and the temperature are assumed to be uniform over each structural component. No such structural components were included in the analysis reported here, and Eq. 6.14 is taken to be zero.

This leaves only the integrals over A_m and A_f to be discussed. Moreover, since Eq. 6.1 is symmetric with respect to its subscripts i and j, the elemental exchange area is to be evaluated only once.

Considering first the fin, that is j = 1 and i = 2, and the fact that over the channel surface the radiosity and the temperature are considered to be functions of axial distance only

$$\int_{A_2} \frac{\partial^2 \overline{s_1 s_i}}{\partial A_1 \partial A_i} (1 - \alpha_{1i}) W_i \, dA_i =$$

$$\int_{z=0}^{z=L} [1 - \alpha_{1i}(z)]\ W_i(z) \int_{\phi=0}^{\phi^*} \frac{\partial}{\partial A_1} \left(\frac{\overline{s_1 s_i}}{\Delta A_i} \right) R d\phi \ dz = \tag{6.15}$$

$$\int_{z=0}^{z=L} [1 - \alpha_{1i}(z)]\ W_i(z)\ SS(z; x_f, z_f)\ dz$$

where L designates the tube length; R and ϕ are the polar coordinates of A_2, with origin on the tube axis, with $\phi = 0$ and $\phi = \phi^*$ representing, respectively, the root of the fin and the contact line between the tube and its tangent plane through the center of ΔA_1 on the fin. The first step in Eq. 6.15 was obtained by integrating over ΔA_1 and subsequently applying the mean-value theorem of integral calculus, while the second step simply defines the exchange function for every point (x_f, z_f) on the fin which was integrated in closed form for the right-circular flow channel. The result is shown in Appendix D.

The exchange function of the tube with respect to the fin is obtained by dividing SS in Eq. 6.15 by $(R_\phi{}^*)$. Thus

$$\int_{A_1} \frac{\partial^2 \overline{s_2 s_i}}{\partial A_2 \partial A_i} (1 - \alpha_{2i})\ W_i\ dA_i =$$

$$\frac{1}{R\phi^*} \int_{z=0}^{L} \int_{x=0}^{H} [1 - \alpha(z, x_f, z_f)]\ W(x_f, z_f)\ SS(z, x_f, z_f)\ dx_f\ dz_f \tag{6.16}$$

For the numerical evaluation of the integrals a suitable quadrature such as the trapezoidal rule is chosen so as to render Eq. 6.7 in this form

$$P_j = \sum_j M_{ji} W_i \qquad (6.17)$$

$$i,j = 1, 2, \ldots, N$$

which is a system of N linear algebraic equations for the $N = (n_x + 1)(n_z + 2)$ unknown values of the radiosity W_i. Here, n_x and n_z are the numbers of subdivisions chosen in the x- and the z-directions, respectively. The vector P on the left-hand side of Eq. 6.17 is called the excitation vector

$$P_j = - \varepsilon_j E_j - (1 - \alpha_{ej})\, q''_{ej} \qquad (6.18)$$

on the right-hand side, the transfer matrix M_{ji} is given by

$$\delta_{ji} - \chi_{\underline{i}} [1 - \alpha_{\underline{ji}}]\, SS_{\underline{ji}} = M_{ji} \qquad (6.19)$$

where

$$\delta_{ji} = \begin{matrix} 0 \\ 1 \end{matrix} \quad \text{for} \quad \begin{matrix} i \neq j \\ i = j \end{matrix}$$

is the Kronecker delta, χ_i is a suitable quadrature coefficient and $SS_{\underline{ji}}$ is given either by Eq. 6.15 or by Eq. 6.16 depending on whether j refers to the fin or to the channel, respectively. There is no matrix multiplication implied in Eq. 6.19, hence the underscores.

In the present program phase, Eq. 6.17 is solved at every time step only when the transfer matrix is sufficiently temperature sensitive, otherwise the transfer matrix is completely inverted only once to yield the unknown radiosity at any time.

$$W_i = \sum_j (M_{ij})^{-1} P_j \tag{6.20}$$

through a simple matrix multiplication. It may be noted that the most significant temperature dependence of optical properties is contained in the excitation vector P_j.

All radiant heat fluxes are normalized with respect to σT_o^4 where T_o designates the reference temperature, that is the fluid inlet temperature. Exchange factors are nondimensional and need not be normalized.

$$w_j = \frac{W_j}{\sigma T_o^4} \quad , \quad \tilde{q}_j = \frac{q_j''}{\sigma T_o^4} \, , \qquad p_j = \frac{P_j}{\sigma T_o^4} \tag{6.21}$$

The nondimensional forms of Eqs. 6.4 and 6.20 are used to compute $\tilde{q}_{net,rad}$ in Eqs. 2.17, 4.11 and 5.5.

7. Aerodynamic Heating

The aerodynamic heating model used to evaluate the convective flux from the radiator surface on the orbiter vehicle is subdivided into three major regimes. The first regime encompasses low speed flow for which the heat transfer coefficients are determined from expressions appearing in standard heat transfer texts for flow over a flat plate. The second regime consists of a model for high speed flow in which the convective heat transfer coefficient is evaluated from an experimental correlation for flow over the upper surface of the shuttle orbiter vehicle (Ref. 9). The third section of the model encompasses a low to high speed transitional flow regime. Within this regime the heat transfer coefficient is an interpolated value that lies between the values obtained in the low and high speed regimes. Calculations for the convective heat flux for all three regimes are based on Eckert's reference enthalpy method (Ref. 10).

Within each of the three regimes the heat transfer coefficient is calculated for cases where the flow is laminar, transitional or fully turbulent. In addition to the evaluation of the heat flux when the flow is forced, the procedure accounts for heat transfer by free convection at times when the shuttle vehicle is stationary or moving with a relatively low velocity.

The program for the evaluation of the aerodynamic heating rate is divided into six sub-tasks each of which is written as a separate subprogram. This procedure allows for changes in the periphery of the program without affecting the program foundation. The basic calculations are carried out in and controlled from the SUBRØUTINE CØNVEC. Atmospheric temperature and speed of sound are evaluated within the SUBRØUTINE ATMØS. Atmospheric properties evaluated at the reference temperature are calculated within the SUBRØUTINE REFP. The orbiter velocity and altitute are evaluated in the FUNCTIØN subprogram ALTVEL. The SUBRØUTINE NUS evaluates the Nusselt number for the radiator system.

It should be noted that the analysis does not account for the effects of shock wave interaction or interference heating caused by flow interference between the orbiter, booster or any supporting structure.

The analysis for the determination of the aerodynamic heating first requires the evaluation of a reference temperature which is used for the determination of all air properties. The reference temperature is a function of the Prandtl number and recovery factor of the air, as well as the vehicle Mach number.

The Mach number in turn is a function of the altitude and velocity of the orbiter at any instant time. Altitude and velocity profiles for the orbiter are contained in data arrays supplied by the user (see Part A-3c of the U Manual. If the value of the Integer I is used to specify either ascent or reentry phase, then the N paired data points which define the velocity V and elevation Z as a function of time t may be expressed functionally as

$$V_i = V_i\ (I,\ t_i) \quad i = 1,2,\ldots,N \tag{7.1}$$

$$Z_i = Z_i\ (I,\ t_i) \quad i = 1,2,\ldots,N \tag{7.2}$$

Once the orbiter velocity and altitude are known as a function of time, the vehicle Mach number M may be calculated from the equation

$$M = \frac{V}{c} \tag{7.3}$$

The speed of sound c is an atmospheric property that is a function only of the altitude.

The reference temperature is a function of the recovery factor r which for laminar flow is

$$r = \sqrt{N_{Pr}}$$

and for turbulent flow (Ref. 11) is

$$r = N_{Pr}^{(8 + 0.528M^2/(22 + M^2))} \tag{7.4}$$

where the Prandtl number N_{Pr} is an atmospheric property. To avoid a discontinuity in the value of the recovery factor between the laminar and turbulent flow models, Eq. 7.4 was used as the expression for the recovery factor for both flow models. The resulting error in the reference temperature was found to be approximately 5 R in an extreme case.

All of the properties for the atmosphere used in the evaluation of the heat transfer coefficient are evaluated at the high speed reference temperature. Eckert (Ref. 10) recommends the expression

$$i^* = 0.5\ (i_\infty + i_w) + 0.11\ r\ (\gamma - 1)\ M^2 i_\infty \tag{7.5}$$

for the reference enthalpy i* which can be converted to the reference temperature T* once the relationship

$$T^* = T^*\ (i^*) \tag{7.6}$$

between the atmospheric enthalpy and temperature is known. The subscripts "∞" and "w" in Eq. 7.5 refer to the enthalpy of the air evaluated at the free stream and surface temperature, respectively, and γ is the ratio of the specific heats for air.

It should be mentioned that when velocities are low ($M \to 0$) Eqs. 7.5 and 6 yield a reference temperature that approaches the film temperature $(T_\infty + T_w)/2$. As a result Eqs. 7.5 and 6 were used to evaluate the reference temperature for all three flow regimes, i.e., low speed, high speed and the transitional regimes.

The convective flux is the product of the convective heat transfer coefficient and the difference between the air enthalpy evaluated at the surface temperature and at the adiabatic wall temperature. The adiabatic wall enthalpy i_{aw} is related to the free stream enthalpy, recovery factor and vehicle velocity by the relationship

$$i_{aw} = i_{\infty} + \frac{rV^2}{2g_c} \tag{7.7}$$

The convective heat transfer coefficient h_i used in the reference enthalpy method may be expressed in terms of the Nusselt number N_{Nu}

$$N_{Nu} = \frac{h_i x c_p^*}{k^*} \tag{7.8}$$

where c_p^* and k^* denote the atmospheric specific heat and thermal conductivity evaluated at the reference temperature T^*. The symbol x denotes a characteristic length of the radiator system which for forced convection is the distance from the stagnation point on the shuttle to the center of the radiator panel.

The expressions for the orbiter Nusselt number selected for the low speed and high speed regime and for laminar, transitional and turbulent flow are summarized in Table 1. Values for the Nusselt number for conditions lying between the low and high speed regimes were obtained by interpolation so that the convective heat flux from the shuttle varies continually from one regime to the other. The symbols N_{Re} and N_{Nu} appearing in the table denote the Reynolds number and Prandtl number, respectively, where

$$N_{Re} = \frac{\rho^* V x}{\mu^*}$$

$$N_{Pr} = \frac{\mu^* c_p^*}{k^*}$$

The "*" superscript on each property indicates that the property is evaluated at the temperature T^*.

TABLE 1

FORCED CONVECTION NUSSELT NUMBER FOR ORBITER

	LOW SPEED REGIME $M \leq 0.5$	HIGH SPEED REGIME $M \geq 1.0$
LAMINAR FLOW $Re < 1.0 \times 10^5$	$N_{Nu} = 0.332\, N_{Re}^{1/2} N_{Pr}^{1/3}$	$N_{Nu} = 0.375\, N_{Re}^{0.5014}\, N_{Pr}$
TRANSITIONAL FLOW $1 \times 10^5 \leq Re \leq 1 \times 10^6$	$N_{Nu} = 6.78 \times 10^{-5} N_{Re}^{1.238} N_{Pr}^{1/3}$	$N_{Nu} = 3.339 \times 10^{-4}\, N_{Re}^{1.111}\, N_{Pr}$
TURBULENT FLOW $Re > 1 \times 10^6$	$N_{Nu} = 0.0288\, N_{Re}^{0.8} N_{Pr}^{1/3}$	$N_{Nu} = 0.0346\, N_{Re}^{0.7746}\, N_{Pr}$

For the low speed regime the expressions for the Nusselt number are those for laminar transitional and turbulent flow over a flat plate (Ref. 6*). Nusselt number relationships for high speed flow regime are taken from Ref. 9 where experimental wind tunnel data are presented for a delta space shuttle orbiter. The data are for leeward surface heat transfer at angles of attack between 10° and 30° and Mach numbers of 8 and 16. The Nusselt number is shown to be relatively independent of angle of attack so that the high speed correlation may be applied to both the ascent phase for which the angle of attack is approximately zero and the reentry phase when the angle of attack may approach 60°. The scatter in the data of Ref. 9 from the selected Nusselt relationships is on the order of 100%.

The leeward surface correlation was selected because the aerodynamic heating rates in this region of the shuttle are relatively low when compared to heating rates for the lower body or windward surface. Estimates place the peak reentry temperature of the lower surface stagnation line around 2100 F while the peak leeward temperature is estimated to be about 600 F (Ref. 12). Therefore, placing the radiator on the upper surface of the orbiter not only will result in a more efficient operation upon reentry, but also will minimize the need for reservicing of the surface coating on the radiator panels.

The aerodynamic heating analysis includes free convection from the radiator surface during pre-launch operation and when the shuttle vehicle is moving with a relatively low velocity. The expression for the free convection Nusselt number is a function of the Grashof Prandtl product where the Grashof number N_{Gr} is given by

$$N_{Gr} = g\beta \left(\frac{\rho}{\mu}\right)^2 y^3 \left(T_w - T_\infty\right)$$

where g represents the acceleration of gravity, ρ, μ and T_∞ are the atmospheric density, dynamic viscosity and temperature, respectively and T_W denotes the radiator surface temperature. The symbol y denotes the overall dimension of the radiator panel in the direction parallel to the acceleration of gravity. Since the atmosphere is assumed to be an ideal gas, the

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coefficient of thermal expansion β is simply the reciprocal of the average absolute temperature of the air

$$\beta = \frac{2}{T_w + T_\infty} \quad .$$

The free convection Nusselt numbers N_{Nu_f} and their applicable ranges of Grashof Prandtl product used for this analysis are

$$N_{Nu_f} = 1.585\ (N_{Gr}N_{Pr})^{0.195} \qquad (10^{-1} < N_{Gr}N_{Pr} < 10^4) \qquad (7.9a)$$

$$N_{Nu_f} = 0.590\ (N_{Gr}N_{Pr})^{0.250} \qquad (10^4 \leq N_{Gr}N_{Pr} \leq 10^9) \qquad (7.9b)$$

$$N_{Nu_f} = 0.130\ (N_{Gr}N_{Pr})^{0.333} \qquad (N_{Gr}N_{Pr} > 10^9) \quad . \qquad (7.9c)$$

The values for the free convection Nusselt number given in Eq. 7.9 were multiplied by the ratio (x/y) and then added to the forced convection Nusselt number to obtain a value that accounts for combined free and forced convection in the low speed regime.

Equations 7.1 through 7.8 combined with the appropriate Nusselt number relationship from Table 1 for forced convection and Eq. 7.9 for free convection are sufficient to determine the convective heat flux into the radiator surface which is given by

$$q''_{aero} = h_i\ (i_\infty - i_{aw}) \quad . \qquad (7.10)$$

The convective flux may be normalized by dividing by the heat flux σT_o^4 or

$$\tilde{q}_{aero} = \frac{h_i \, (i_\infty - i_{aw})}{\sigma T_o^{\,4}} \tag{7.11}$$

where T_o is the fluid temperature at the inlet plane to the flow channel. The normalized convective heat flux given by Eq. 7.11 is used in the energy equation for both the fin (Eq. 2.18) and the meteoroid protection layer (Eq. 5.5).

C. DESIGN PARAMETERS

Certain design parameters are necessary for the design specification, for the selection of the optimum radiator system and even the system definition as required for the heat transfer analysis. In the following are discussed, in that order, the prediction of the meteoroid protection layer thickness, the system weight and a collection of nondimensional groups which define the radiator system, the operational conditions, and the performance characteristics.

8. Meteoroid Protection Thickness

In this section an engineering equation is developed to predict the thickness of a meteoroid protection layer required to cover all radiator surfaces that might be damaged by the impact of a meteoroid. Several assumptions have been made during the derivation. They are:

1. The meteoroid particle is spherical.
2. The meteoroid flux is isotropic.
3. Poissons distribution law describes the probability of an impact of a meteoroid.

It should be mentioned that any equation used to predict meteoroid protection thickness is only as accurate as the experimental data used in that equation. Even though much information has been published in recent years concerning protection theories, there is still considerable question as to the density, velocity and mass distribution of meteoroid particles in outer space. In addition to these uncertainties, two basic models for penetration theory have been proposed within the last decade and there appears to be no close agreement between the two. Experimental verification of either model has been hampered by the fact that particle velocities used in experimental tests have only recently approached the meteoroid velocity range. In short, an extremely reliable theory for the prediction of protection layer thickness does not presently exist.

Structural materials that can be used in this study as a protection layer are copper, aluminum and beryllium. While both copper and aluminum were selected primarily as fin and tube materials due to their superior heat transfer characteristics, beryllium was chosen for its protection capabilities. The penetration theory predicts a protection layer thickness that decreases as the modulus of elasticity increases. Therefore, beryllium becomes an attractive protection material due to its high modulus of elasticity and its relatively low density. In fact studies (Refs. 13 and 14) have shown that beryllium can significantly reduce protection layer weight.

The basic equation (Ref. 15) for the depth of penetration of a meteoroid particle into a target of infinite depth is

$$P_{\infty} = \gamma\, d \left(\frac{\rho_p}{\rho_t}\right)^{\phi} \left(\frac{\bar{V}}{\bar{c}}\right)^{\theta} \tag{8.1}$$

where

- γ empirical constant generally accepted to be in the range of 1.5 to 2.5
- ρ_p density of the meteoroid particle
- ρ_t density of the target material
- $\bar{V}$ velocity of the meteoroid particle
- $\bar{c}$ velocity of sound in the target material
- d diameter of the meteoroid particle
- ϕ constant between 1/3 and 2/3
- θ constant between 1/3 and 2/3

The ratio of the meteoroid velocity and the velocity of sound in the target represents a target Mach number. The velocity of sound in the target can be expressed in terms of the modulus of elasticity

$$\bar{c} = \sqrt{E_t g_c / \rho_t} \tag{8.2}$$

where

- E_t modulus of elasticity of the target material
- g_c proportionality constant relating mass units to force units
- ρ_t target density

If the meteoroid particle is assumed to be spherical, the diameter may be written in terms of its mass

$$d = \left(\frac{6M_p}{\pi\rho_p}\right)^{1/3} \tag{8.3}$$

where

M_p meteoroid mass

ρ_p meteoroid density

The probability that an exposed surface will be struck by a meteoroid during a period of time can only be determined after the distribution of meteoroids of a given mass is known. This information is usually given in the form of an equation such as

$$F = \alpha M_p^{-\beta} \tag{8.4}$$

where

F cumulative number of impacts of particles with mass M or larger per unit area per unit time

M_p mass of the meteoroid particle.

The symbols α and β represent experimentally determined constants. Published (Ref. 16) values of α and β vary over a considerable range, but they lie within the limiting values,

$$1.3 \times 10^{-15} < \alpha < 2.54 \times 10^{-9} \qquad [\mathrm{ft}^2 \ \mathrm{day} \ \mathrm{gm}^{-\beta}]^{-1}$$

$$1.11 < \beta < 1.34 \qquad [\mathrm{Dimensionless}] \quad .$$

The cumulative number of impacts on a surface with a vulnerable area of A during a mission time of τ by a meteoroid of mass M_p of larger is then

$$N = FA\tau = A\tau\ \alpha\ M_p^{-\beta} \quad .$$

It is generally assumed (Ref. 17) that meteoroids are randomly distributed in outer space and that each collision can be described by Poissons probability law. From the Poisson distribution function, the probability of zero events occurring P_o when the average number of events is N is

$$P_o = e^{-N}$$

or

$$\ln P_o = -N \quad .$$

Substituting the value for N gives the probability that no meteoroid of mass M or larger will impact on the surface of area A during time τ of

$$\ln P_o = A\tau\alpha \, M_\rho^{-\beta}$$

or

$$M_p = \left(\frac{\alpha A\tau}{-\ln P_o} \right)^{1/\beta} \quad . \tag{8.5}$$

To account for the fact that all meteoroids do not strike the protection layer normally, the meteoroid velocity $\bar{V}$ may be replaced by a critical velocity $\bar{V}_c$ where

$$\bar{V}_c = \bar{V}(\cos \lambda)^n \tag{8.6}$$

λ angle between the direction of $\bar{V}$ and the normal to the protection surface

n an experimentally determined constant.

If n is selected to be unity the damage to the protection layer caused by an oblique collision is based on the meteoroid's normal component of velocity. A more conservative approach would be to set n = 0 in which case all particles are considered to impact normally.

If the meteoroid flux is assumed to be isotropic the angle dependence may be replaced by

$$(\cos \lambda)^n = \left(\frac{2}{3n\theta\beta+2}\right)^{1/3\beta} \quad . \tag{8.7}$$

Finally account must be taken for the fact that the meteoroid will not impact on an infinite target, but one with a finite thickness. As a result even though the meteoroid may not penetrate the protection layer, spalling may damage the radiator panel. To account for spalling the thickness of meteoroid protection t used should be larger than the predicted penetration into an infinite target or

$$t = aP_\infty \tag{8.8}$$

Accepted values of a lie between 1.5 and 2.0.

Equations 8.1 through 8.7 may now be substituted into Eq. 8.8 to give an expression for the meteoroid protection layer thickness. The result is

$$t = a\gamma\left(\frac{6}{\pi}\right)^{1/3} \left(\frac{\alpha A\tau}{-\ln P_o}\right)^{1/3\beta} \rho_p^{-1/3} \left(\frac{\rho_p}{\rho_t}\right)^{\phi} \left(\frac{V}{12(E_t g_c/\rho_t)^{1/2}}\right)^{\theta} \left(\frac{2}{3n\theta\beta+2}\right)^{1/3\beta} \tag{8.9}$$

where

- t - thickness of protection layer (inches)
- a - experimental constant (dimensionless)
- γ - experimental constant (dimensionless)
- α - experimental constant that relates meteoroid flux to mass (gm/(day ft^2))
- β - experimental constant that relates meteoroid flux to mass (dimensionless)

A - vulnerable area requiring protection (ft^2)

τ - mission time (days)

P_o - probability of no damage caused by impact of meteoroid (dimensionless)

ρ_p - density of meteoroid particle (gm/cm^3)

ρ_t - density of protection layer (lb_m/ft^3)

$\bar{V}$ - velocity of meteoroid (ft/sec)

E_t - modulus of elasticity of protection material (lb_f/in^2)

g - 32.174 $lb_m ft/lb_f sec^2$

θ - experimental constant (dimensionless)

ϕ - experimental constant (dimensionless)

n - experimental constant that describes penetration depth as a function of angle of incident (dimensionless).

Selection of Values for Experimental Constants

Values for the experimental constant ρ, β, ρ_p and $\bar{V}$ used in Eq. 8.9 were selected from the Manned Spacecraft Center publication for meteoroid environment criterion (Ref. 18).

The values for α and β for meteoroids having a mass between 1 gm 10^{-6} gm used in Eq. 8.4 are

$$\alpha = 1.888 \times 10^{-10} \qquad gm^{\beta}/(ft^2 day) \tag{8.10}$$

$$\beta = 1.213 \tag{8.11}$$

The average meteoroid density is

$$\rho_p = 0.5\ gm/cm^3 \tag{8.12}$$

and the average meteoroid velocity is

$$\bar{V} = 20 \text{ km/sec.} \tag{8.13}$$

Values chosen for the remaining constants appearing in Eq. 8.9 are summarized in Table 2. Values of these constants are also listed in the table that will yield optimistic (minimum) and pessimistic (maximum) thicknesses for the meteoroid protection layer.

	Recommended Value	Pessimistic Value	Optimistic Value
a	1.75	2.0	1.5
γ	1.50	2.5	1.5
ϕ	1/2	1/3	2/3
θ	2/3	2/3	1/3
n	1.0	0	1.0

TABLE 2. Empirical Constants for Meteoroid Protection Layer Thickness

The following is an analysis of the sensitivity that the meteoroid protection layer thickness has to the uncertainty in the values of the five parameters listed in Table 2. This information will enable the user to judge his selection of these constants from within the recommended ranges.

An expression for the error in the meteoroid protection thickness may be obtained by taking the logarithm of Eq. 8.9 followed by differenting the resulting equation. This process yields the equation

$$\frac{dt}{t} = \frac{da}{a} + \frac{d\gamma}{\gamma} + \phi\left(\frac{\rho_p}{\rho_t}\right)\frac{d\phi}{\phi} + [\theta \ln\left(\frac{V}{\bar{c}}\right) - \frac{n\theta}{3n\theta\beta+2}]\frac{d\theta}{\theta} - [\frac{n\theta}{3n\theta\beta+2}]\frac{dn}{n} \quad . \tag{8.14}$$

If the symbol E_a is selected to represent the relative error in the meteoroid protection thickness resulting from a relative uncertainty in the value for the parameter a, then it is evident from Eq. 8.14 that

$$E_a = \frac{dt/t}{da/a} = 1.0$$

when all other parameters are held constant. Similarly the error caused by an uncertainty in the value of γ will be

$$E\gamma = \frac{dt/t}{d\gamma/\gamma} = 1.0 \quad .$$

When the value for θ is taken to be the recommended value of 2/3 and β is set equal to the value fixed by MSC's environmental model (Eq. 8.11), the resulting error in the meteoroid protection layer thickness due to an uncertainty in the value for n is

$$E_n = \frac{dt/t}{dn/n} = -\left(\frac{n\theta}{3n\theta\beta+2}\right) = -0.15 \quad .$$

The magnitude of the error for the final two parameters ϕ and θ are a function of the material selected for the protection layer. In order to give an indication of the range of errors that can be expected for various protection materials, the errors were calculated for the three structural materials that were selected in the program: aluminum, beryllium and copper. If the meteoroid particle density is assumed to be fixed at the value recommended by the MSC environmental model (Eq. 8.12), then an uncertainty in the value of ϕ from the recommended value of 1/2 would cause an error in the protection thickness of

$$E_\phi = \frac{dt/t}{d\phi/\phi} = \phi \ln \left(\frac{\rho_p}{\rho_t}\right)$$

which for each of the three structural materials results in the following errors

$$E_\phi = -0.85 \qquad \text{aluminum}$$
$$E_\phi = -0.65 \qquad \text{beryllium}$$
$$E_\phi = -1.44 \qquad \text{copper.}$$

The high density and low modulus of elasticity of copper makes its protection characteristics rather undesirable. For this reason the error of 1.44 indicated for copper probably will never be experienced in practice, and this value should be considered as a limiting case.

An uncertainty in the value of θ from the recommended value of 2/3 would cause an error in the protection layer thickness equal to

$$E_\theta = \frac{dt/t}{d\theta/\theta} = [\theta \ln (\frac{\bar{V}}{c}) - \frac{n\theta}{3n\theta\beta+2}]$$

which for each of the three structural materials is:

$$E_\theta = 0.77 \qquad \text{aluminum}$$
$$E_\theta = 0.20 \qquad \text{beryllium}$$
$$E_\theta = 1.01 \qquad \text{copper.}$$

The errors calculated in the analysis are summarized in Table 3.

TABLE 3. Ratio of Relative Error in Thickness to Relative Uncertainty in Empirical Constants

Protection Material / Parameter	Aluminum	Beryllium	Copper
a	1.0	1.0	1.0
γ	1.0	1.0	1.0
ϕ	-0.85	-0.65	-1.44
θ	0.77	0.20	1.01
n	-0.15	-0.15	-0.15

If the error values for copper are excluded, the protection thickness is most sensitive to variations in the parameters a and γ and least sensitive to variations in the parameter n. Even though the protection thickness is least sensitive to the selection of n, it should be noted that the 100% variation between the optimistic and pessimistic value of n is the largest of all of the parameters. Also it should be noted that the signs on the values in Table 3 indicate that an increase in the parameters a, γ and θ result in an increase in the protection layer thickness, while an increase in the values for ϕ and n result in a decrease in the protection layer thickness. This fact can be verified by the choice of the values of each of the parameters listed in Table 2. The values labeled as those which will produce a pessimistic value for the protection thickness are maximum values for a, γ and θ and minimum values for ϕ and n.

To further evaluate the effect the meteoroid protection thickness has on the performance of the fin system, the temperature of the coolant fluid at the exit plane of the flow channel was evaluated first under the "pessimistic" conditions for the meteoroid protection layer, second for the "recommended" conditions and finally for the "optimistic" conditions. The results of these computer runs are shown below.

Case	Protection Layer Thickness-Inches	Normalized Outlet Fluid Temperature T/T_o
Pessimistic	0.377	0.8855
Recommended	0.063	0.8922
Optimistic	0.020	0.8932

Even though the thickness of the meteoroid protection layer varies by nearly a factor of 20, the resulting error in the enthalpy drop is only

$$\frac{0.8932 - 0.8855}{1 - 0.8922} \cdot 100\% = 7.15\% \quad .$$

9. The Mass of the System

The system mass is computed, firstly as a convenience for the user and secondly for the purpose of the planned system optimization. The system mass includes

(i) the mass of the fluid in all tubes

$$M_c = n_t \frac{d^2\pi}{4} \int_o^L \rho_c dz = n_t \rho_{c,o} \frac{d^2\pi}{4} L \int_o^1 \nu d\zeta \tag{9.1}$$

(ii) the mass of the fins

$$M_f = n_t H L \rho_f (s_r + s_t) \tag{9.2}$$

(iii) the mass of all tubes

$$M_w = n_t s_w L \cdot \pi (d + s_w) \rho_w \tag{9.3}$$

and

(iv) the mass of the protection layer

$$M_m = n_t s_m L \rho_m [\pi(d + s_w + s_m) - s_r] \tag{9.4}$$

but it does not include the thermal coating nor the mass of the manifold and the fluid in the manifold. In Eqs. 9.1 through 4 represent

- n_t the number of tubes
- d the tube diameter
- ρ the density
- L the tube length
- H the fin height, distance between fin root and fin tip
- s the thickness

while the subscripts designate ρ and s as follows

- c coolant fluid
- f fin

m meteoroid protection layer

r fin root

t fin tip

w tube wall

o inlet condition.

The integral in Eq. 9.1 is time-dependent and evaluated at the initial conditions.

10. Nondimensional System Parameters

The governing equations in the preceding radiator system analysis are developed in non-dimensional form for the purpose of (i) reducing the number of parameters, (ii) evolving the set of relevant parameters, and (iii) presenting the results in a general form which is applicable to groups of systems rather than an individual system. A summary of parameters is presented here for the detailed analysis discussed in the preceeding chapters.

The transient flow field is the coolant channel and the temperature field over the fin can be represented as functions of:

a) the independent variables

time $$\tau = \frac{tw_o}{L} \tag{10.1}$$

axial coordinate $$\zeta = \frac{z}{L} \tag{10.2}$$

radial coordinate $$\eta = \frac{2r}{d} \tag{10.3}$$

transverse coordinate normal to the channel axis $$\xi = \frac{x}{H}$$

b) the dependent system variables

fin temperature $$\theta_f\ (\xi,\zeta;\tau\ ) = \frac{T_f}{T_o} \tag{10.4}$$

channel temperature $$\theta_w\ (\eta,\zeta;\tau\ ) = \frac{T_w}{T_o} \tag{10.5}$$

meteroid protection layer temperature $$\theta_m\ (\eta,\zeta;\tau\ ) = \frac{T_m}{T_o} \tag{10.6}$$

coolant fluid temperature $$\theta_c\ (\zeta;\tau\ ) = \frac{T_c}{T_o} \tag{10.7}$$

coolant fluid pressure $\pi(\zeta,\tau) = \frac{p}{p_o}$ (10.8)

coolant fluid velocity $\omega(\zeta;\tau) = \frac{w}{w_o}$. (10.9)

The solution to the problem will depend on the geometry of the system, the material properties and the definition of operational conditions. There was no attempt made to establish similitude with respect to the material properties because the scaling laws would either be too restrictive to allow for general property variations or too complex (for instance, the concept of corresponding states for gases). Consequently, the ϕ-parameters defined in Eqs. 3.27 through 3.30, in Eq. 4.4 and in Eqs. 5.1, 2 and 6 are omitted from this summary; they constitute temperature and pressure variation of properties. This leaves the following list of parameters, in addition to n, the number of tubes:

c) <u>the geometric parameters</u>

fin height-to-length ratio $\bar{H} = \frac{H}{L}$ (10.10)

fin profile slope $c = \frac{s_r - s_t}{2H}$ (10.11)

fin root thickness $\bar{s}_r = \frac{s_r}{H}$ (10.12)

tube diameter-to-length ratio $\delta = \frac{d}{L}$ (10.13)

channel wall thickness $\bar{s}_w = \frac{2s_w}{d}$ (10.14)

protection layer thickness $\bar{s}_m = \frac{2s_m}{d}$ (10.15)

d) <u>the operational parameters</u>

coolant flow Reynolds number $$N_{Re} = \frac{dw_o}{\nu_o} \quad \text{(10}$$

Prandtl number
(representing coolant selection) $$N_{Pr} = \left(\frac{\mu c_p}{k_c}\right)_o \quad \text{(10.}$$

inlet pressure heat $$F_p = \left(\frac{p}{\rho w}\right)_o \quad \text{(10.1}$$

compressibility $$\bar{Q}_o = \frac{\pi n \rho d^2 c_p}{4\sigma T_o^3} \quad \text{(10.1}$$

inlet coolant power flux $$F_z = \left(\frac{p}{\rho c_p T}\right)_o \quad \text{(10.20}$$

where n is the number of tubes

incident radiant heat flux $$\bar{Q}_{rad} = \frac{\alpha_o q''}{\varepsilon_o \sigma T_o^4} \quad \text{(10.2}$$

meteoroid velocity $$M_m = \frac{v_m}{c_m} \quad \text{(10.2}$$

protection layer density
(representing selection of
protection layer material) $$\phi_\rho = \frac{\rho_{mt}}{\rho_m} \quad \text{(10.2}$$

where ρ_{mt} is the density of the meteoroids.

Similarity for ascent and reentry operations is difficult to establish unless one restricts oneself to similar velocity-altitude profiles which can be represented by the

max. Mach number $$M_{max} = (v/c)_{max} \tag{10.24}$$

and its corresponding (through same altitude)

Reynolds number $$(N_{Re})_{\infty} = \frac{\rho_{\infty} v L}{\mu_{\infty}} \tag{10.25}$$

Prandtl number $$(N_{Pr})_{\infty} = \frac{\mu_{\infty} c_{p\infty}}{k_{\infty}} \tag{10.26}$$

Grashof number
(before launch) $$N_{Gr} = \frac{g L^3 \beta \Delta T}{\nu^2}$$

This completes the list of non-dimensional groups resulting from the detailed analysis.

D. Extension of the Analysis to Related Systems

11. Non-Symmetrical Heating

The purpose of this section is to describe a segment of the program which is intended to extend the application of the radiator simulation to non-symmetrical flow conditions in adjacent tubes. This program will also account for, in an approximate manner, a radiator panel which does not lie in one plane, or a panel which consists of U-shaped tubes.

In the original simulation of the radiator system, it was assumed that the coolant fluid entering all tubes has identical properties. As a result, the operating conditions and heat loss is determined for a single fin segment between two adjacent tubes and these conditions are assumed to exist for all other fin segments. In reality, this situation will exist only when all tubes are fed by a relatively large manifold whose flow rate and temperature entering each tube is unaffected by the removal of coolant fluid at each succeeding channel entrance.

The actual flow situation could possibly be far from the idealized case which was assumed to exist because it leads to a simplified mathematical model. A manifold of realistic size will lose heat by radiation from its surface and by conduction into the fin elements so that the coolant fluid entering individual flow channels will experience a difference in temperature. Furthermore, unless the manifold is carefully reduced in size after passing each tube inlet, neighboring tubes will not receive identical mass flow rates. Also, two adjacent tubes may be fed by the outlet flow from separate fuel cells which may be operating under different load conditions causing non-symmetrical conditions in adjacent fin panels. In short, a situation where two tubes receive fluid at different inlet conditions is to be expected.

For the purpose of extending the application of the main program to situations discussed above, a series of program units were written and integrated into the main program unit. These programs calculate the location of the adiabatic plane on a fin which separates two tubes having different inlet flow rates and temperatures. The fin height to the adiabatic plane is then used as input to the main program. The calculations with the main program remain unaffected since the mathematical model requires only that the input value given for the fin height is that distance from the tube to the location of the adiabatic plane.

The analysis considered here may also account for, in an approximate fashion, fin elements that do not lie in one plane. If the radiator panel is wrapped around a cylindrical structural component (Fig. 3a) adjacent fin panels will be under the influence of different effective sink temperatures. In this analysis the assumption is made that the regular breaks in the radiator panel occur at the adiabatic plane between the tubes rather than at the tubes themselves (Fig. 3b) which is probably the most reasonable location. If the cylindrical panel is composed of numerous tubes and the curvature is gradual, the difference between the two cases should be negligible.

The program accepts two sink temperatures supplied by the user or it calculates the correct sink temperature from the MRI incident flux data. The analysis of this section assumes steady state, one-dimensional conduction in an untapered fin. The fin may radiate from one or both sides when the fin panel is in one plane. When the panel is curved the fin is assumed to radiate only from the convexed surface. Fluid and fin properties are assumed constant at the inlet conditions. No convection from the fin surface and no radiant blocking of the tubes is considered. The only incident fluxes considered in this analysis are those accounted for in the MRI program; i.e. solar, earth and earth albedo.

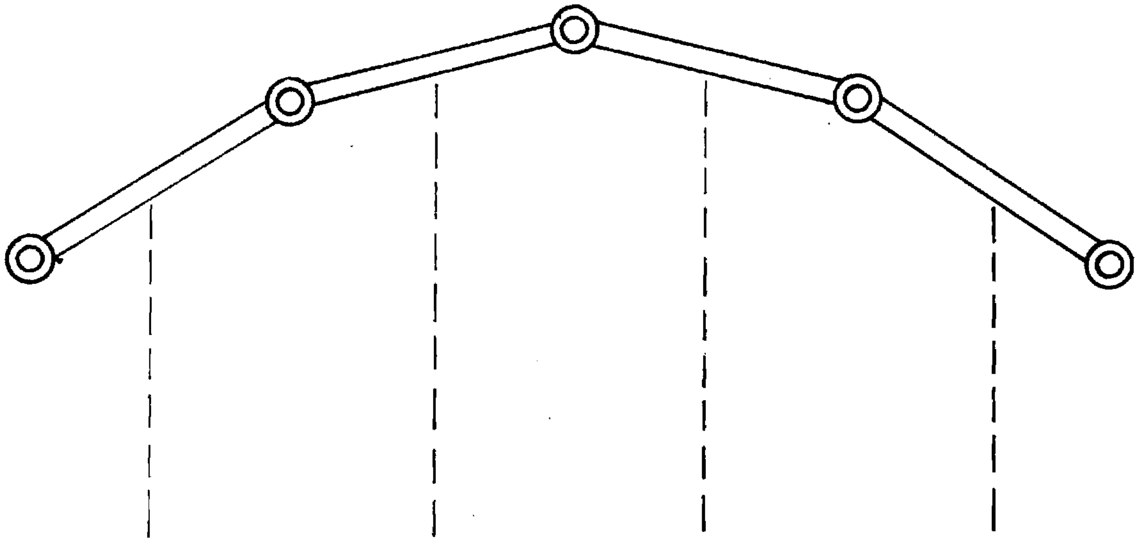
The user is cautioned that the analysis considered here assumes a one dimensional model and as such represents an approximation to the actual operating conditions of the non-symmetrical radiator. This caution is particularly applicable to the panel that contains U-shaped tubes, because this situation can lead to a highly two dimensional condition.

The analysis considers the ith tube of a radiator panel of thickness t, inside tube diameter d, tube length L_i and distance between tubes of 2H (Fig. 4). The energy transfered from the ith tube carrying fluid with an inlet temperature of T_{oi}, specific heat of c_p and mass flow rate of $\dot{m}_i$ is

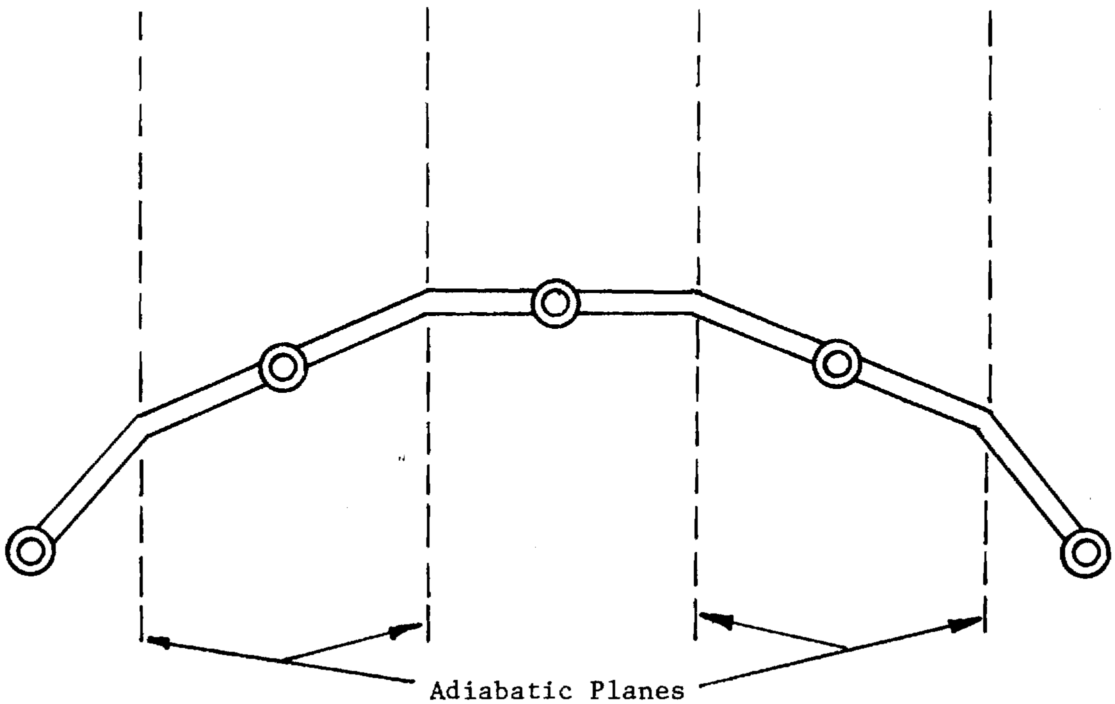
$$q_i = \dot{m}_i \; c_p \; (T_{oi} - T_{bi}) \; (1 - e^{-U_i}) \tag{11.1}$$

The quantity U_i is given by

$$U_i = \frac{\pi d h_i L_i}{\dot{m}_i c_p} \tag{11.2}$$



(a) Fin Segments Inclined At Tube Locations-
Geometry For Physical Model.



(b) Fin Segments Inclined At Location Of Adiabatic
Planes-Geometry For Mathematical Model

Fig. 3

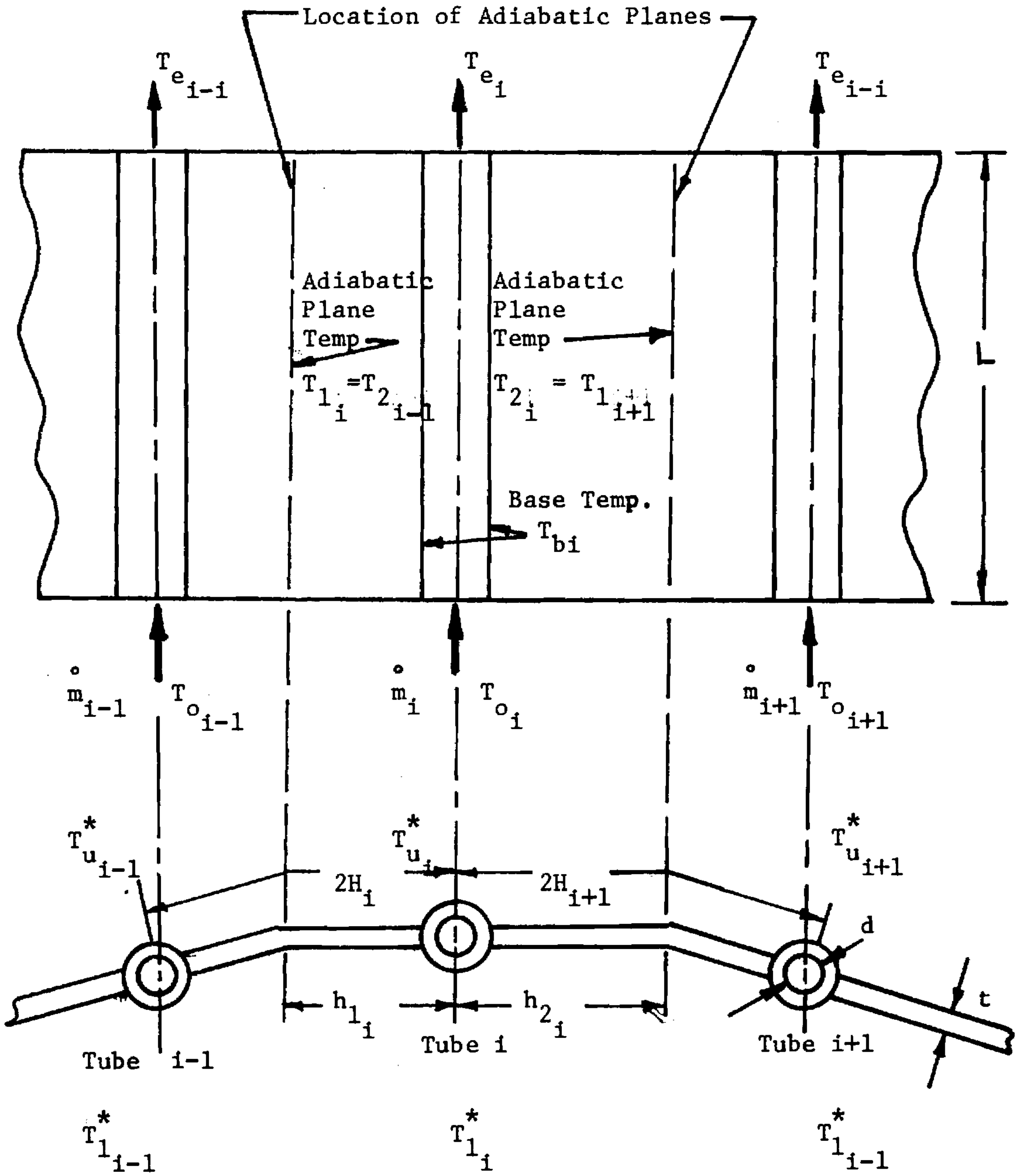


Figure 4. Fin Geometry for Non-Symmetrical Panel

where h_i is the convective heat transfer coefficient of the fluid in the tube and Tb_i is the average fluid bulk temperature (also assumed to be the fin root temperature.)

The convective heat transfer coefficient h_i in Eq. 11.1 is evaluated from the Nusselt number which is related to the Reynold and Prandtl numbers by the expressions

$$N_{Nu} = 5 + 0.025\ (N_{Re} N_{Pr})^{0.8} \quad \text{for} \quad \begin{cases} N_{Pr} < 0.1 \\ N_{Re} > 2300 \end{cases} \tag{11.3 a}$$

$$N_{Nu} = 0.023\ (N_{Re}^{0.8} N_{Pr}^{0.3}) \quad \text{for} \quad \begin{cases} N_{Pr} > 0.1 \\ N_{Re} > 2300 \end{cases} \tag{11.3 b}$$

$$N_{Nu} = 3.65 + \frac{0.0668[N_{Re} N_{Pr} (d/L)]}{1 + 0.045[N_{Re} N_{Pr} (d/L)]^{2/3}} \qquad N_{Re} \le 2300 \tag{11.3 c}$$

The heat rejected from the coolant fluid given in Eq. 11.1 under the assumption of steady state and one-dimensional heat transfer can be determined by calculating the net radiant loss from the fin surfaces. If one side of the ith fin surface is radiating to an environment with an effective sink temperature of T_i^* then

$$\begin{aligned} q_i = {} & \eta_{1i}\ \epsilon\ h_{1i}\ L_i\ \sigma\ (T_{bi}^4 - T_i^{*4}) \\ & + \eta_{2i}\ \epsilon\ h_{2i}\ L_i\ \sigma\ (T_{bi}^4 - T_i^{*4}) \end{aligned} \tag{11.4}$$

where η_{1i} and η_{2i} are the fin effectivenesses for the fin attached to the left and right of the ith tube, respectively, and h_{1i} and h_{2i} are the distances between the tube centerline and the adiabatic plane for the fin attached to the left and right of the ith tube.

When the fin radiates from both sides, the effective sink temperatur will be different for both sides and the net radiative flux will be

$$q_i = 2\eta_{1i}\, \epsilon\, h_{1i}\, L_i\, \sigma\, (T_{bi}^4 - T_i^{*4})$$

$$+ 2\eta_{2i}\, \epsilon\, h_{2i}\, L_i\, \sigma\, (T_{bi}^4 - T_i^{*4}) \tag{11.5}$$

where the sink temperature T_i^{*4} becomes

$$T_i^* = \left(\frac{T_{ui}^{*4} + T_{\ell i}^{*4}}{2} \right)^{1/4} \tag{11.6}$$

The subscripts u and ℓ in Eq. 11.6 denote the sink temperatures for the upper and lower surfaces of the fin respectively.

The fin effectiveness in Eqs. 11.4 and 11.5 is a function of the conductance parameter N_c and the ratio of the sink temperature to base temperature T^*/T_b or for the ith tube

$$\eta_{1i} = \eta\, (N_{c1i},\ T_i^*/T_{bi}) \tag{11.7}$$

$$\eta_{2i} = \eta\, (N_{c2i},\ T_i^*/T_{bi}) \tag{11.8}$$

The conductance parameter is defined as

$$N_{c1i} = \frac{\epsilon\, \sigma\, T_{bi}^3\, h_{1i}^2}{Kt} \quad \text{and} \tag{11.9}$$

$$N_{c2i} = \frac{\epsilon\, \sigma\, T_{bi}^3\, h_{2i}^2}{Kt} \tag{11.10}$$

where K is the thermal conductivity of the fin material.

In addition to having a continuous slope in the fin temperature profile at the adiabatic plane, the fin temperature must also be continuous at this plane. For a one dimensional fin the temperature at the adiabatic plane T is a function of the conductance parameter and the ratio of sink temperature to base or

$$T = T\ (N_c,\ T^*/T_b) \tag{11.11}$$

As the program searches for the position of the adiabatic plane, the distances between the tube centerline and adiabatic plane is systematically varied until the fin tip temperatures given by Eq. 11.11 for two adjacent tubes are equal. As an example, consider the ith and i+1 tube. Using the subscript 1 to denote a fin segment attached to the left of a tube and the subscript 2 to denote the fin segment attached to the right of a tube, the tip temperature profile will be continuous when

$$T_{2i} - T_{1i+1} \longrightarrow 0$$

If the difference in these two tip temperatures is denoted by δ_i, then δ_i becomes a function of T_{2i} and T_{1i+1}. By combining Eq. 11.11 and the definitior of N_c these two tip temperatures may be specified by the functional relationshi

$$T_{2i} = f\ (T_{bi},\ h_{2i}) \qquad \text{and} \tag{11.12}$$

$$T_{1i+1} = f\ (T_{bi+1},\ h_{1i+1}) \tag{11.13}$$

The fin base temperatures of the ith and i+1 tube can be determined by Eqs. 11.7 through 11.9 or written functionally

$$T_{bi} = f\ (h_{1i},\ h_{2i}) \qquad \text{and} \tag{11.14}$$

$$T_{bi+1} = f\ (h_{1i+1},\ h_{2i+1}) \tag{11.15}$$

If Eqs. 11.12 through 11.15 are combined, the difference in the two temperatures δ_i may be expressed as

$$\delta_i = \delta_i\ (h_{1i},\ h_{2i},\ h_{1i+1},\ h_{2i+1}) \tag{11.16}$$

But from the geometry of the radiator system

$$h_{1i} = 2H_i - h_{2i-1} \qquad \text{and} \tag{11.17}$$

$$h_{1i+1} = 2H_{i+1} - h_{2i} \tag{11.18}$$

where $2H_i$ and $2H_{i+1}$ is the distance between the centerlines of tubes i-1 and i and tubes i and i+1, respectively.

By combining Eqs. 11.17 and 11.18 with Eq. 11.16, the final functional relationship for the difference in the fin temperatures at the adiabatic plane is given by

$$\delta_i = \delta_i\ (h_{2i-1}, h_{2i}, h_{2i+1}) \tag{11.19}$$

In other words δ_i can be expressed entirely in terms of the distance from tube centerline to the adiabatic plane for the tube under consideration plus the same distance for tubes on either side.

The approach to the solution for the location for all adiabatic planes is one which gives $\delta_i = 0$ for all i tubes. The program utilizes a Newton iteration to determine an appropriate change in ith adiabatic plane Δh_i. Written in matrix notation, the relationship between Δh_i and the difference in tip temperatures δ_i is

$$[\delta_i] = [P_{ij}][\Delta h_i] \tag{11.20}$$

where the elements of the matrix p_{ij} are given by

$$[P_{ij}] = \frac{\partial \delta_i}{\partial h_j} \tag{11.21}$$

and the elements of the vector Δh_i are given by

$$\Delta h_i = h_i^{k+1} - h_i^{k} \tag{11.22}$$

where k denotes the k th iteration used to find a set of adiabatic plane locations for all fin elements which result in $\delta_i = 0$ for all i tubes. A mathematical subroutine is used to invert the matrix $[p_{ij}]$ so that the values for all adiabatic planes may be calculated from

$$[\Delta h_i] = [p_{ij}]^{-1} [\delta_i] \tag{11.23}$$

Once the distance to all adiabatic planes have been determined for all tubes which lead to continuous tip temperatures and continuous, zero slopes at the fin tips, the net heat transfer q_i from each fin segment may be determined from Eqs. 11.5 through 11.10. The exit fluid temperature from each tube T_{e_i} may then be determined from

$$q_i = \dot{m}\, cp(T_{e_i} - T_{o_i}) \tag{11.24}$$

Since the main program unit requires only a single distance between the tube centerline and the adiabatic plane, the two distances h_{1_i} and h_{2_i} must be averaged to yield a single value. The averaging process produces a value $\bar{h}_i$ which results in the same heat transfer for the symmetrical fin. This single value for each tube is calculated by using equation (11.5) resulting in

$$\bar{h}_i = \frac{\eta_{1_i} h_{1_i} + \eta_{2_i} h_{2_i}}{\eta_{1_i} + \eta_{2_i}} \tag{11.25}$$

As previously defined, the subscripts 1 and 2 denote the two halves of the fin attached to both sides of the ith tube. Values for the fin effectiveness are evaluated from Eq. 11.7.

The program considers the case of the radiator panel with U-shaped tubes to be approximated by three sequential parallel tube sections.

The program first calculates the fin base temperature and the distance to the adiabatic plane for the first section of the three tube segments. The heat transferred from the fluid is then calculated from

Eq. 11.1. The outlet fluid temperature from the first tube T_e segment is then calculated from the expression

$$q = \dot{m}\, c_p (T_e - T_o)$$

The exit fluid temperature simply becomes the inlet fluid temperature to the second tube segment (the base of the U). The same process is repeated for the remaining two tube segments resulting in two more values for the distance to the adiabatic plane. The single value for the distance to the adiabatic plane necessary for entry to the main program unit is determined from an average weighted with respect to the length of each tube segment.

E. Property Fundamentals

The fundamental principles used to prepare the required thermo-physical properties for inclusion into the computer code are exhibited in this chapter while the specific details concerning the materials treated in this program phase are placed into the appendices.

The principles involved are those of macroscopic thermodynamics treated in most elementary texts. The approach of deriving analytic expressions for the required properties is not unique because the starting point is dictated by the availability of experimental data. The result, however, must be of the same form regardless of whether, for instance, the coolant fluid is gaseous or liquid.

The properties of the structural materials are the least problematic ones since they depend on the temperature at most; and the standard polynomial collocation methods are entirely sufficient. Care must be exercised, however, that the collocation imply continuous fourth derivatives for highest integration efficiency or, less desirable, at least continuous representation of the property itself which may exclude piecewise allocation of degrees higher than one.

What is said about the properties of structural materials holds in principle for the description of the atmosphere whose properties depend only on altitude. Even though the optical properties of the thermal coating depend, in general, on wave-length and temperature, the spectral dependence is integrated into the averaged ("gray") properties (see Eqs. 6.5 and 6), and the results are functions of one variable, the temperature. Consequently, there remains but the discussion of the coolant fluid properties which depend strictly on two state variables.

In macroscopic thermodynamics there are required two equations of state for the description of a substance, namely the thermal equation of state $f(\rho,p,T) = 0$ which relates any one of density ρ, pressure p and temperature T to the remaining two, and the caloric equation of state, perhaps in the form of $c_v^o = f(T)$ where c_v^o is the zero-pressure specific heat at constant volume. These two equations are sufficient to develop all of the required thermodynamic functions, namely:

(i) specific heat at constant pressure $c_p(\rho,T)$

(ii) isobaric thermal expansion coefficient $\beta(\rho,T)$

(iii) isothermal bulk modulus $\kappa(\rho,T)$

(iv) enthalpy $h(\rho,T)$

These functions are discussed in Section 12.

The transport properties, namely the thermal conductivity $k(\rho,T)$ and the dynamic viscosity $\mu(\rho,T)$ are correlated on the basis of residuals as explained in Section 13. The properties of the atmosphere are dealt with in Section 14.

12. Thermodynamic Properties

The first step in developing thermodynamic properties is to secure a thermal equation of state

$$f(p,\rho,T) = 0 \quad . \tag{12.1}$$

For almost all pure gases and air, this equation can be found in the literature, either in the form suggested by Benedict-Webb-Rubin (virial expansion) or in that suggested by Beattie-Bridgeman. Both equations are explicit in p,

$$p = p(\rho,T) \tag{12.2}$$

so that κ is immediately obtained from Eq. 11.2 by implicit differentiation

$$\kappa(\rho,T) = \frac{1}{\rho}\left(\frac{\partial\rho}{\partial p}\right)_T \tag{12.3}$$

which can be evaluated as $\kappa(p,T)$ after inversion of Eq. 11.2 into

$$\rho = \rho(p,T) \quad . \tag{12.4}$$

The inversion of Eq. 12.2 is facilitated by computing $(\partial p/\partial\rho)_T$ from Eq. 11.2 and subsequently applying the Newton-Raphson method along the specified isotherm with temperature T in Eq. 12.4

The isobaric thermal expansion coefficient

$$\beta = -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_p$$

is also obtained by implicit differentiation of Eq. 12.2 while keeping the left-hand side constant.

After having collocated the zero-pressure specific heat at constant volume; that is, c_v^o (T) by a power polynomial in T, one obtains first the specific heat at constant volume

$$c_v(\rho,T) = c_v^o\,(T) - T \int_o^{\rho} \left(\frac{\partial^2 p}{\partial T^2}\right)_{\rho} \frac{d\rho'}{(\rho')^2} \tag{12.5}$$

and then the specific heat at constant pressure

$$c_p(\rho,T) = c_v(\rho,T) + \frac{T\beta^2}{\rho\kappa} \quad . \tag{12.6}$$

The derivative in Eq. 12.5 is obtained from Eq. 12.2; and β and κ are both function of ρ or p and T.

Finally the enthalpy h is calculated from its definition

$$h\ (\rho,\ T) = \frac{p}{\rho} + u\ (\rho,\ T) \tag{12.7}$$

where the internal energy u may be obtained by two successive integrations, the first one along an isotherm (over ρ), and the second one along an isochore (over T):

$$u = u(\rho_o,T_o) + \int_{T_o}^{T}\int_{\rho_o}^{\rho} c_v(\rho',T')d\ 'dT' + \int_{\rho_o}^{\rho} [p - \frac{T\beta}{\kappa}]\ \frac{d\rho'}{(\rho')^2} \tag{12.8}$$

Liquids can be treated, in principle, as gases; except that the equation of state, Eq. 12.1, is rarely available. One may find, with little difficulty the zero-pressure isobaric expansion coefficient $\beta_o = c(T)$, and then represent adequately the isothermal bulk modulus by

$$\kappa(p,T) = a(T) + b(T)\ p \quad . \tag{12.9}$$

Under any circumstances, one must satisfy

$$\left(\frac{\partial\beta}{\partial p}\right)_T + \left(\frac{\partial\kappa}{\partial T}\right)_p = 0 \tag{12.10}$$

which yields, form Eq. 12.9

$$\beta(p,T) = -a'p - \frac{b'}{2} p^2 + c \qquad (12.11)$$

where primes indicate differentiation with respect to T, of the polynomials a(T) and b(T) in Eq. 12.9. Equations 12.9 and 11 yield for the density

$$\rho(pT) = \rho(0,T_o)e^{[a(T)p + \frac{1}{2} b(T)p^2 - \int_{T_o}^{T} c(T')dT']} . \qquad (12.12)$$

The specific heats and the enthalpy are to be derived as for gases (see Eqs. 12.6 and 7). Other possibilities are to develop κ from the speed of sound and the ratio of specific heats; but the reader is warned not to imply $\kappa = 0$ or $c_p = c_v$, unless there is sufficient evidence to support these assumptions.

13. Transport Properties

While the thermal conductivity k and the dynamic viscosity μ of liquids may often times be adequately represented by functions of temperature T alone (facilitated by polynomial collocation), these same properties for gases depend on density as well. It is recognized that the difference, or residue

$$\psi_1(\rho) = k(\rho,T) - k^*(T) \tag{13.1}$$

between the thermal conductivity $k(\rho,T)$ and the low-pressure thermal conductivity $k^*(T)$ depends only on the density. Similarly, for the dynamic viscosity

$$\psi_2(\rho) = \mu(\rho,T) - \mu^*(T) \ . \tag{13.2}$$

Hence k and μ can be represented by the sum of two polynomials, one in ρ and the other in T. The residuals ψ_1 and ψ_2 are published for a number of gases or may be developed from property data (Ref. 19 for N_2 and He).

14. Atmospheric Properties

For the prediction of aerodynamic heat fluxes incident on the radiator system during ascent and reentry (see Section 7) the evaluation of the following atmospheric properties are required:

- Temperature
- Pressure
- Density
- Molecular Weight
- Speed of Sound
- Viscosity
- Thermal Conductivity
- Specific Heat at Constant Pressure
- Enthalpy

The model for these atmospheric properties is presented in two sections. The first covers altitudes from sea-level to 301,000 feet. Within this range the molecular weight is assumed to be constant and the temperature variation with altitude is a sequence of connected line segments. The second section of the model covers altitudes above 301,000 feet where the molecular weight decreases linearly with altitude. For this altitude range the approximate polynomial expressions for density and pressure suggested in Part 4 of Ref. 20 were used. Errors between the values given by the approximate expression and the 1962 Standard Model are less than 5% over the entire range of altitudes.

Atmospheric air is assumed to be an ideal gas for all altitudes. Therefore compressibility effects at low altitudes are neglected. The error in computed densities resulting from the ideal gas assumption may be as high as 0.05% for altitudes below 6 miles, but becomes less than 0.01% above 12 miles (Ref. 20). The air is also assumed to be in hydrostatic equilibrium.

All properties except geopotential altitude, specific heat and enthalpy are evaluated from expressions presented in Refs. 20 and 21. The expression for geopotential altitude was taken from Ref. 22, while specific heat and enthalpy data were taken from Ref. 23.

The model developed for the atmospheric properties is considered to be applied to altitudes up to 100 miles and to latitudes between 30 and 60^{o}N. It is anticipated that atmospheric properties are not needed for altitudes exceeding 100 miles, because the convective heat flux from the fin system will be negligible at this altitude and above.

The properties for the earth's atmosphere are known with increased uncertainty as the altitude increases. In fact, the 1962 Standard Atmosphere (Ref. 21) consists of four regions as follows:

0 - 20 km	Standard
20 - 32 km	Proposed Standard
32 - 90 km	Tentative
90 - 700 km	Speculative

Any uncertainty in the atmospheric properties will naturally be reflected as an error in the convective heat flux on the shuttle vehicle. Fortunately during the ascent phase of the shuttle operation the convective flux from the radiator system is fairly small compared to the radiative flux by the time the shuttle has approached altitudes for which the atmospheric properties are considered to be "speculative"; on the other hand during re-entry, significant convective fluxes are known to exist at altitudes above 90 km. As a result every effort should be made to revise the existing atmospheric property model at high altitudes as new data become available.

The atmospheric model is based on several primary constants. The sea-level pressure, temperature, molecular weight, density and acceleration of gravity and the universal gas constant were assigned the fixed values of

$$P_o = 2116.22 \text{ lbf/ft}^2$$
$$T_o = 518.67 \text{ R}$$
$$M_o = 28.9644$$
$$\rho_o = 0.07647 \text{ lbm/ft}^3$$
$$g_o = 32.1741 \text{ ft/sec}^2$$
$$R^* = 1545.31 \text{ ft lbf/lb mole R}$$

Properties for Altitudes Less than 301,000 feet.

a. Geopotential Altitude - H

The state variables for air are expressed in terms of the single variable, the geopotential altitude

$$H = \int_0^Z \frac{g(z)}{g_o} dz =$$

$$Z - 1.573126 \times 10^{-7}Z^2 + 2.4656553 \times 10^{-14} Z^3$$
$$- 3.8667054 \times 10^{-21}Z^4 + 6.0621354 \times 10^{-28}Z^5$$
$$- 9.5013649 \times 10^{-35}Z^6 \qquad (14.1)$$

where Z is the geometric altitude in meters, g_o is the acceleration of gravity at sea-level and g(Z) denotes the local acceleration of gravity. See Ref. 22 for details.

b. Temperature - T

The general expression of the temperature as a function of geopotential altitude is

$$T = T_b + L(H - H_b) \qquad (14.2)$$

T_b and H_b are the endpoints of straight-line segments representing T(H) and are listed, together with L(H) in the following table.

c. Molecular Weight - M

The molecular weight is constant at a value of 28.9644.

d. Pressure - P

Within a region where the temperature varies linearly, the ideal equation of state and the hydrostatic yield the following expressions for

H_b (km)	L (K/km)	T_b (K)
0		288.15
	- 6.5	
11		216.65
	0.0	
20		216.65
	1.0	
32		228.65
	2.8	
47		270.65
	0.0	
52		270.65
	-2.0	
61		252.65
	-4.0	
79		180.65
	0.0	
90		180.65

TABLE 4. Lapse Rate and Base Temperatures for Atmospheric Model

pressure:

$$\frac{P}{P_b} = \left[\frac{T_b}{T_b + L(H - H_b)} \right]^{\frac{g_o M_o}{R^* L}} \qquad (L \neq 0) \tag{14.3}$$

$$\frac{P}{P_b} = \exp \left[- \frac{g_o M_o (H - H_b)}{R^* T_b} \right] \qquad (L = 0) \tag{14.4}$$

i.e $11 \leq H \leq 20$ km
$47 \leq H \leq 52$ km
$79 \leq H \leq 90$ km

The subscript "o" denotes a quantity evaluated at sea-level and the subscript "b" denotes a quantity evaluated at the base of one of the straight line segments of the atmospheric model.

c. Density - ρ

The density may be calculated from the ideal equation of state once the temperature and pressure have been evaluated.

$$\rho = \frac{MP}{R^* T} \tag{14.5}$$

f. Speed of Sound - c

The speed of sound was evaluated from the expression

$$c = \left[\gamma \frac{R^* T}{M} \right]^{1/2} \tag{14.6}$$

For altitudes less than 301,000 feet the ratio of specific heats is taken to have a fixed value of 1.40.

g. Viscosity - μ

The dynamic viscosity was evaluated from the expression

$$\mu = \frac{\beta T^{3/2}}{T + S} \tag{14.7}$$

where

$$\beta = 1.458 \times 10^{-6} \quad \frac{\text{kg}}{\text{sec m(K)}^{1/2}}$$

and

$$S = 110.4 \text{ K}$$

h. Specific Heat at Constant Pressure c_p and Enthalpy i

Values for c_p and i between the temperatures of 100 R and 6400 R were taken from the standard Gas Tables (Ref. 23) and placed in the program in tabular form. A value of c_p and i at any temperature intermediate to a pair of tabular values was determined by an interpolation routine (see Section III 4).

Properties for Altitudes Greater than 301,000 Feet

a. Pressure - P

The pressure for altitudes between 301,000 and 528,000 feet is based on the polynomial approximation given in Part IV of Ref. 20. The pressure is written in terms of the sea-level pressure P_o in the form

$$P = P_o \left\{ \sum_{n=0}^{11} [A_n Z^n]^{-4} \right\} \tag{14.8}$$

where Z is the geometric altitude and values for A_n appear in Table 4.1 of Ref. 20.

b. Density - ρ

The density is written in terms of a similar polynomial

$$\rho = \rho_o \left\{ \sum_{n=0}^{11} [B_n Z^n]^{-4} \right\} \tag{14.9}$$

where values of B_n appear in Table 4.1 of Ref. 20.

c. Molecular Weight - M

The molecular weight is assumed to vary linearly with altitude Z (see Fig. I.2.7 in Ref. 21). The resulting expression for M is

$$M = 28.9644 - 0.030949\ (Z - 90)$$

whre Z is in km.

d. Temperature - T

The temperature is calculated from the values for pressure, density and molecular weight indicated above from the ideal equation of state

$$T = \frac{PM}{\rho R^*}$$

e. Speed of Sound - c

For altitudes greater than 301,000 feet the equation for the speed of sound is the same one as used for the lower altitudes, but the ratio of the specific heats is no longer assumed to be equal to 1.40. The ratio of the specific heats varies with the molecular weight according to the expression

$$\gamma = \frac{c_p}{c_p - R^*/M}$$

The remaining properties are calculated using identical expressions to those outlined for altitudes less than 301,000 feet.

III. NUMERICAL TECHNIQUES

1. Introduction

The analysis carried out in Chapter II lead, as far as the mathematical problem formulation is concerned, to three initial value problems and one matrix manipulation. The three initial-value problems are to establish

(1) the initial conditions for the coolant fluid, defined by Eqs. 3.42 through 3.45,

(ii) the dynamics of the coolant flow, defined by Eqs. 3.40 through 42 and 44,

(iii) the temperature field throughout the system, defined by Eqs.2.18 through 2.22 for the fin, Eqs. 3.39 and 46 for the coolant, Eqs. 4.6, 7 and 8 for the channel wall, Eqs. 4.7, 5.3 and 5 for the protection layer, or Eq. 4.11 replacing Eqs. 2.19, 4.6, 7 and 8 and 5.3 and 5 in the case where Eq. 4.9 is satisfied. These equations must be supplemented by the specification of the initial, non-dimensional temperature everywhere in the system.

Each initial-value problem is solved by a fourth-order Runge-Kutta-Simpson integration discussed in Section III-2.

The radiosity equation, Eq. 6.17 requires the matrix manipulation, namely either the solution of a system of linear algebraic equations, or a matrix inversion whenever the optical properties of the thermal control coating are considered temperature independent. Either task is accomplished by elementary row operations which transform, in a single process, the augmented coefficient matrix into a row-reduced echelon matrix. The reader is referred for this trnasformation to standard texts on linear algebra (Ref. 9).

Additional mathematical operations are programmed as subprograms which may be generally applied and which are discussed in Sections III-3 through III-7 in this order: an evaluation of polynomials in one variable, an Aitken interpolation, first and second differentiation, definite integration and integration with variable upper integration limit for functions of equally spaced arguments, and solution to system of linear algebraic equations.

2. The Runge-Kutta-Simpson Integration

Two types of initial-value problems are to be solved in this program. The first type includes Item (i) and (ii) mentioned in the Introduction, namely the fluid dynamics exclusive of the transient fluid temperature field, and involves ordinary, first-order differential equations, linear in the derivatives with respect to the axial distance ζ, that is Eqs. 3.42, 43 and 44. The equations are solved explicitly for these derivatives so as to take on the general form of Eq. 2.1:

$$\frac{dy_i}{dx} = f_i(x, y_1, y_2, \ldots, y_n) \tag{2.1}$$

$$y_i(0) = a_i \qquad , \; i = 1, 2, \ldots, N \tag{2.2}$$

Equation 2.2 constitutes the appropriate initial conditions. The other type of initial-values problem, mentioned as item (iii) in the Introduction, involves partial differential equations which are linear and of the first order in the time-derivatives; moreover, all equations, Eqs. 2.18, 3.46, 4.8 and 5.3, are explicit in the time derivatives. Having subdivided the radiator system into intervals, equally spaced in each appropriate domain (fluid, wall, fin, etc.), and then written the different equations corresponding to each one of the resulting N interior nodal points, one may discretize the spatial derivatives occurring on the right-hand sides of the partial differential equations. The result is a set of ordinary differential equations, with time as the independent variable but of a form which is identical to Eq. 2.1. Equation 2.2 is given by the initial temperature distribution; a uniform temperature was chosen for the first start of the integration ($a_i = a$; $i = 1, 2, \ldots, N$), subsequent integrations during optimization runs are expected to start from the previously computed steady-state temperature distributions. The boundary conditions may be satisfied in three different ways. Either, the temperatures are computed directly from the finite-difference equation representing the boundary conditions at the end of every time step, or secondly, the boundary conditions may be included into the system of Eqs. 2.1 after differentiation with respect to time, or lastly, an equation of the form of Eqs. 2.1 may be derived directly from a control volume bounded at one side by the boundary of interest. All three possibilities have been utilized.

Discretization introduces obviously a truncation error; all spatial derivatives are represented consistently with a truncation error proportional to the square of the local spatial interval (see Sect. III 5) but higher order terms may be included anytime by modifying a single program unit each for the first and second derivatives.

The system of Eqs. 2.1 and 2.2 is solved by a fourth-order Runge-Kutta integration, that is if the f_i in Eqs. 2.1 have continuous fourth-order derivatives, the time-related accuracy of the integration is of order four (Refs. 26 and 27). Under much weaker conditions, namely uniform Lipschitz continuity, Ref. 26, the accuracy is still first-order and stability is secured. It may be noted that the Lipschitz continuity is also the prerequisite for uniqueness of the solution to Eqs. 2.1.

An existing single-precision, floating-point Runge-Kutta-Simpson subprogram, SUBROUTINE RKS, written by R. Schubert at the Aerospace Corporation was used. Its fixed-step integration mode was employed for the integration of the fluid flow variables along the channel axis, while the transient temperature field was integrated with variable time steps, chosen automatically so as to keep the "truncation error" per time step below a specified limit. The absolute and relative errors A_i and R_i are specified, by the user, for each variable y_i, and after every Runge-Kutta integration step a Simpson integration is carried out over the same interval and with the intermediate derivatives as used in the former integration. From the difference D_i between the two integrations is calculated the "truncation error" measure

$$E_m = \max E_i = \left| \frac{D_i}{A_i + R_i \, |y_i|} \right| \quad , \qquad i = 1, \ldots, N \tag{2.3}$$

and if $0.75 < E_m$ then the time step DEL is divided by $\sqrt[5]{10}$ and the step is repeated, if $0.075 < E_m \leq 0.75$ then DEL is multiplied by $\sqrt[5]{10}$ for the subsequent step.

All variables y_i are set equal to their initial values in the program which calls RKS. During the integration RKS interacts directly with two other subroutines, namely DERIV and CNTRL, whose names are the first elements of the argument list in the call statement. The first subroutine, DERIV, serves to compute all N derivates dy_i/dx in accordance with Eqs. 2.1. The second subroutine, CNTRL, controls the output during integration and the termination of integration. Output of current values of all variables along with important system parameters is provided under two different integration modes: general transient system simulation, MSTØR = 0 in NAMELIST/RUNØPT/, produces output in arbitrarily chosen, fixed time steps, DTWRTE, up to the final time TEND, both specified in NAMELIST/RUNØPT/ and in hours; the second mode serves to compute the steady-state conditions and is invoked by setting MSTØR = 1 and by specifying the number LIMWRT of time intervals DTWRTE at which output is desired.

The integration under the second mode (MSTØR = 1) is terminated as soon as the expected truncation error due to program termination is less than five times the specified relative error per time step, RLIMIT, that is R_i in Eq. 2.3. The largest truncation error associated with the j-th time step is anticipated on the basis of Eqs. 1.1 and 2 in Section II as follows

$$\delta_j = \max_i \delta_{i,j} = \max_i \left\{ \Delta_j \tau \frac{\dot{y}_{i,j}}{\ln \dfrac{\dot{y}_{i,j-1}}{\dot{y}_{i,j}}} \right\} , \quad i = 1,2,\ldots, N \qquad (2.4)$$

The maximum is taken from all N modal points, $\Delta_j\tau$ is the current integration step size with index j, and $\dot{y}_i$ stands for the dy_i/dx in Eqs. 2.1.

The argument list of RKS (and RKSF) is as follows:

(i) DERIV, name of derivative subroutine } declared as EXTERNAL
(ii) CNTRL, name of control subroutine } in calling program

(iii) Y , array name*, containing the y_i's in Eqs. 2.2 **

(iv) DY, array name*, containing the dy_i/dx in Eqs. 2.1

(v) A , array name*, containing the A_i's in Eq. 2.3 **

(vi) R , array name*, containing the R_i's in Eq. 2.3 **

(vii) T , the independent variable X in Eqs. 2.1 **

(viii) DEL, the integration step**, DEL $\neq$ 0

(ix) N , (integer) the number of equations**

(x) IFVD = 0: variable step size**, see Eq. 2.3
= 1: fixed step size equal to DEL

(xi) IBKP = 0: adjust step size at most once before repeat,**
= 1: adjust in accordance to Eq. 2.3

(xii) NTRY = 1: continue integration**, normal start
= 2: return from RKS
= 3: repeat last step with new DEL
= 4: restart
} to be changed in CNTRL

(xiii) IERR = 0, normal integration
= -1 indicates singularity when IFVD = 0
= +1 indicates denominator vanishes in Eq. 2.3 at some time during integration.

(xiv) through (xx) are array names* with which the user need not be concerned except YS that contains the y's in 2.1 at the previous times step: DELY, PD, SD, YS, YST, DYST, YSIMP.

The SUBRØUTINE DERIV communicates with RKS only via its argument list which contains, in this order, Y, DY, and T, as specified above under iii, iv, and vii. Here, the current values of Y and T are supplied to DERIV, and the corresponding values of DY returned by DERIV to RKS.

The SUBRØUTINE CNTRL communicates with RKS also via its argument list. It contains Y, DY, DEL, T, NTRY, IFVD as specified above under iii, iv, viii, vii, xii and x, respectively. From the array Y are available for output all the results of integration. The time step may be modified to reach a specific time value; and by specifying NTRY one controls the integration process from

---

*Declared in calling program as array with dimension size equal to the number of differential equations.

**To be specified prior to the calling statement.

variable to fixed step size during the integration by resetting IFVD.

This completes the discussion of the integration of both ordinary and partial differential equations as they occur in the analysis developed in Chapter II. The discussion is deemed sufficient to enable the user to apply the RKS routine to other problems as well.

3. The Evaluation of Polynomials

All polynomials

$$z = a_o + a_1 x + a_2 x^2 + \ldots + a_N x^N \qquad (3.1)$$

are carried out in a function subprogram based on the simple, efficient recurrence relation

$$z_o = a_N$$

$$z_{i+1} = x \cdot z_i + a_{i+1}$$

$$i = 0,1,\ldots, N-1 \qquad (3.2)$$

$$z = z_N$$

The coefficients a, i = 0, 1, ...,N must be placed, in the calling program, into an array of dimension (N + 1), N is an arbitrary positive integer.

The procedure is coded as a function subprogram called PØLY(N,A,X), where X is the argument x in Eq. 3.1, A is the array containing M = N + 1 elements starting with A(1) = a_0.

4. Aitken Interpolation

Experimental data and supporting computer results which are not represented by analytic expressions are interpolated by Aitkens interpolation technique (Ref. 27). An (n + 1)-point Largangian interpolation is reduced to a sequence of 1/2 n (n + 1) linear interpolations. The interval spacing is arbitrary; and any number M > n of ordered pairs (x_i, y_i) can be supplied in the calling program. The n points of interpolation are spaced equally about the point x of interpolation. It should be noted, however that unless n = N or n = 2 the result y(x) is not continuous in general. Care must also be taken that all nodes $x_1, x_2, \ldots$ are distinct.

The procedure is coded as a function subprogram called YINT(X,Y,M,N,P), where X and Y are the names of arrays that have the same dimension M and contain the ordered pairs(x_i, y_i), i = 1,2,..., M such that $x_1 < x_2 < \ldots x_M$. The number n of points used for the interpolation is specified as N, and the value of x at which to interpolate is supplied as P. Note that $2 \leq N \leq M$ must be satisfied.

5. Numerical Differentiation

The first and second derivative of tabulated functions of equally spaced arguments is carried out in SUBRØUTINE DDX(Y,DY,DX,N) and in SUBRØUTINE D2DX2(Y,D2Y,DX,N), respectively. Each subroutine requires that two arrays be declared in a DIMENSIØN statement in the calling program, to have at least N elements; one array for the set of ordinates $Y \rightarrow y_i$ supplied by the calling program, the other array for the return of the results, that is $DY \rightarrow dy_i/dx$ or $D2Y \rightarrow d^2y_i/dx^2$. The argument interval Δx and the number of ordinances y_i are to be specified as DX and N, respectively. However, in order that terms of order Δx be retained including at the endpoints of the domain, N must be no less than 3 for DDX and 4 for D2DX2. The truncation error is of order $y'''(\Delta x)^2$ and $y^{IV}(\Delta x)^2$, respectively, for DDX and D2DX2.

6. Numerical Integration

The definite integral

$$F = \int_{X_1}^{X_N} y(x_i)dx \quad , \quad 1 \leq i \leq N; \qquad N \geq 2$$

and the indefinite integral

$$G_j = \int_{X_1}^{X_j} y(x_i)\ dx + G(x_1)$$

$$1 \leq i \leq N \quad ; \quad 1 < j \leq N \ ; \quad N > 3$$

of a tabulated function y_i of an equally spaced argument, x_i, $x_1 + \Delta x$, $x_1 + 2\ \Delta x, \ldots, x_1 + (N - 1)\Delta x$ is carried out by a modified Simpson integration in the FUNCTIØN DEFINT(Y,DX,N) Subprogram and in the SUBRØUTINE FINT(Y,YO,DX,N,F), respectively.

For DEFINT the ordinates y_i are to be placed in the array Y whose dimension of no less than N elements must be declared in the calling program. The argument interval and the number of ordinates are specified as DX and N, respectively.

For FINT there are two array declarations necessary in the calling program, both for at least N elements; one for the integrand $Y \to y_i$ and the other for the integral $F \to G_i$. The integration constant $G(x_1)$, the argument interval and the number of ordinates are to be supplied as YO, DX and N, respectively.

The truncation error of composite Simpson integration is

$$\frac{x_1 - x_N}{180} (\Delta x)^4\ y^{(iv)}\ (\xi) \quad \text{with} \quad x_1 \leq (\xi) \leq x_N.$$

7. Solution to Systems of Linear Algebraic Equations

Systems of linear algebraic equations are solved by the Gauss-Jordan elimination process. The same technique is used to invert matrices.

Consider the system of n linear algebraic equations

$$\sum_{j=1}^{n} A_{ij}X_j = y_i \ .$$

The solution is obtained by performing that sequence of elementary row operations on the augmented coefficient matrix

$$\left(\begin{array}{ccccc} A_{11} & A_{12} & \cdots & A_{1n} & y_1 \\ A_{21} & & & \vdots & y_2 \\ \vdots & & & \vdots & \vdots \\ A_{n1} & & & A_{nn} & y_n \end{array}\right)$$

which leads to the row-reduced echelon matrix

$$\left(\begin{array}{cccccc} 1 & 0 & \cdots & & 0 & x_1 \\ 0 & 1 & & & \vdots & x_2 \\ \vdots & & \ddots & 0 & \vdots & \vdots \\ \vdots & 0 & & \ddots & 0 & \vdots \\ 0 & & & 0 & 1 & x_n \end{array}\right) .$$

Elementary row operations are defined by

(i) multiplication of a row by the scalar $c \neq 0$

(ii) replacement of the r-th row by the r-th row plus c times the s-th row; $c \neq 0$, $r \neq s$; $r,s \leq n$

(iii) interchange of any two rows.

The augmented coefficient matrix consists of the coefficient matrix A_{ij} in the first n columns and the known column vector y_i in its last, (n+1)-st column. The row-reduced echelon matrix has the properties that

(i) the first non-zero element in each non-zero row is 1,

(ii) every zero-row occurs below every non-zero row,

(iii) if the first r rows, $i = 1,2, \ldots, r$ have their non-zero entry in column k_i then the k_i's satisfy $k_1 < k_2 < \ldots < k_r$.

In our specific case, the row-reduced echelon matrix has the identity matrix in place of the coefficient matrix.

When a matrix is inverted then the augmented coefficient matrix consists of the n x n coefficient matrix in its first n columns and the n x n identity matrix in the second n columns, $j = n+1, n+2, \ldots, 2n$. The process indicated above leads n x n identity matrix in the first n columns and the inverted coefficient matrix in the second n columns, from $j = n+1$ through $j = 2n$.

The particular elementary row operations required are

(i) division of the i-th row by A_{ii},

(ii) subsequent multiplication of the resulting i-th row by the element A_{ki} of the k-th row,

(iii) and subsequent replacement of the k-th row by the difference between the k-th row and the i-th row.

This process has to be repeated, essentially, for each row $i = 1, \ldots, n$.

IV RECOMMENDATIONS AND CONCLUSIONS

The analysis described in this report has been successful in simulating the transient heat transfer characteristics of a radiator system under operational conditions expected in flight. The analysis serves as a basis for a rigorous computer program that has been systematically sub-divided into modular subprograms. The modular concept facilitates repeated simulation runs with different structural materials, meteoroid protection material, coolant fluids, and thermal control coatings.

The program predicts the net system heat rejection, the fin, tube and fluid temperature profiles, fluid pressure field as well as the meteoroid protection layer thickness and mass of the entire system. Optimization of the system performance may be achieved through enumeration of the parameter sets.

The program has been thoroughly checked and run for a large number of different simulation cases. A sample representation of these cases may be found in reference [29]. These sample runs have aided in the design of the radiator system during ascent, reentry, transient orbital and steady state orbital conditions. As a result of these computer runs it is recommended that an unprotected radiator not be used during reentry phases of the shuttle operation, because during reentry the aerodynamic heating has been found to exceed the ability of the radiator to reject heat. Also experience gained from the sample runs has shown that the rigorous analysis should not be used for parameter studies of the heat rejection system until a satisfactory optimum domain has been identified by the use of the Simplified Analysis [30]. Displays of typical results are presented in that report.

APPENDIX A

STRUCTURAL MATERIAL PROPERTIES

The thermodynamic and mechanical properties of all materials which make up the radiator system are summarized in Appendices A through C.

Appendix A contains properties for the three structural materials: copper, aluminum and beryllium. Copper and aluminum are intended to be used primarily as fin and tube material, while beryllium was selected for a meteoroid protection material. Four properties are evaluated for each material: specific heat at constant pressure, thermal conductivity, modulus of elasticity, while (1/k) (dk/dT) is computed by differentiating the thermal conductivity relationship with respect to temperature.

Appendix B contains properties for four coolant fluids: helium, Dow Corning 200 Silicon oil, the liquid metal NaK, and two 3-M Company fluorochemical liquids FC-43 and FC-75. Six properties are evaluated for each coolant fluid: isobaric thermal expansion coefficient, isothermal compressibility, specific heat at constant pressure, enthalpy, thermal conductivity and dynamic viscosity. In addition, two equations of state are included for each fluid, one explicitly in density and one explicit in pressure, while the property (1/k) (dk/dT) is computed by differentiating the thermal conductivity relationship with respect to temperature.

Appendix C contains the total hemispherical emittance and two auxiliary radiative properties used in the program for the surface coating Z-93.

All property relationships listed in these Appendices are presented in analytical form obtained by fitting a power polynomial through the data points. The data points listed in the tables are taken from the reference entered before each table. Numerical techniques used for the curve fitting process are explained in Section III.

The polynomial expression for each property has been compared with the referenced data and within the listed temperature range has been found to deviate by no more than the percentage error indicated.

I. COPPER

1. Specific Heat

Reference: Touloukian, Y. S., "Thermophysical Properties of High Temperature Solid Materials," Thermophysical Properties Research Center, Purdue University, Vol. 1, 1967, pp. 456-7.

Data Points:

T	C_p
600 R	0.0920 Btu/(lbm R)
1000	0.0975
2000	0.1112

Polynomial Fit:

Temperature Range: 400 to 2000 R

Equation:

$$C_p = (0.08375 + 1.375 \times 10^{-5}\ TR^{-1}) \times 32.174\ \text{Btu/(slug R)} \quad (A.1)$$

Maximum Error: There was no difference between the computed value and the input data within the accuracy of the computer.

2. Thermal Conductivity

Reference: Touloukian, Y. S., "Thermophysical Properties of High Temperature Solid Materials," Thermophysical Properties Research Center, Purdue University, Vol. 1, 1967, pp. 458-9.

Data Points:

T	k	
600 R	228.369	Btu/(hr ft R)
800	225.708	
1000	222.805	
1200	219.418	
1400	215.306	

Polynomial Fit:

Temperature Range: 500 to 1800 R

Equation:

$$k = (228.369 - 2.62067\ \theta - 0.04033\ \theta^3)\ \text{Btu/(hr ft R)} \tag{A.2}$$

where

$$\theta = \frac{T - 600.0R}{200.0R} \tag{A.3}$$

Maximum Error: 0.87%

3. Temperature Variation of Thermal Conductivity

Eq. A.2 was differentiated with respect to temperature to yield

$$\frac{1}{k}\frac{dk}{dT} = \frac{1}{200}\frac{(-2.62067 - 0.121\ \theta^2)}{(228.369 - 2.62067\ \theta - 0.04033\ \theta^3)}\ R^{-1} \tag{A.4}$$

4. Modulus Elasticity:

Reference: "Material Manual," TRW Equipment Laboratories, February 1966, Report No. ER-6756, Contract No. NAS 9-4884, Fig. 50.

Data Points:

t	Y
0 F	16.55×10^6 lbf/in^2
400	14.35
800	9.65
1200	3.82

Polynomial Fit:

Temperature Range: 500 to 1600 R

Equation:

$$Y = (16.55 - 0.4933\ \theta - 1.935\ \theta^2 + 0.2283\ \theta^3) \times 1.44 \times 10^8\ (\text{lb f/ft}^2) \tag{A.5}$$

where

$$\theta = \frac{T - 459.67\ R}{200\ R} \tag{A.6}$$

Maximum Error: 0.44%

II. ALUMINUM 7075

1. Specific Heat

Reference: Touloukian, Y. S., "Thermophysical Properties of High Temperature Solid Materials," Thermophysical Properties Research Center, Purdue University, Vol. 2-11, 1967, pp. 810-11.

Data Points:

T	c_p	
400 R	0.182	Btu/(lbm R)
600	0.209	
800	0.226	
1000	0.244	
1200	0.270	

Polynomial Fit:

Temperature Range: 300 to 1200 R

Equation:

$$c_p = (0.182 + 0.03616\,\theta - 0.011417\,\theta^2 + 0.00233\,\theta^3 - 0.000083\,\theta^4) \times 32.174 \text{ Btu/(slug R)} \tag{A.7}$$

where

$$\theta = \frac{T - 400 \text{ R}}{200 \text{ R}} \tag{A.8}$$

Maximum Error: 0.34%

2. Thermal Conductivity

Reference: Touloukian, Y. S., "Thermophysical Properties of High Temperature Solid Materials," Thermophysical Properties Research Center, Purdue University, Vol. 2-11, pp. 812-13.

Data Points:

T	k
400 R	88.50 Btu/(hr ft R)
600	100.395
800	105.96
1000	104.024
1200	99.18

Polynomial Fit:

Temperature Range: 300 to 1200 R

Equation:

$$k = (88.5 + 13.0665\ \theta + 0.33275\ \theta^2 - 1.758\ \theta^3 + 0.25375\ \theta^4)\ \text{Btu/(hr ft R)} \tag{A.9}$$

where

$$\theta = \frac{T - 400\ R}{200\ R} \tag{A.10}$$

Maximum Error: 0.96%

3. Temperature Variation of Thermal Conductivity

Equation A.9 was differentiated with respect to temperature to yield

$$\frac{1}{k}\frac{dk}{dT} = \frac{1}{200}\;\frac{(13.0665 + 0.6655\ \theta - 5.25\ \theta^2 + 1.015\ \theta^3)}{(88.5 + 13.0665\ \theta + 0.33275\ \theta^2 - 1.758\ \theta^3 + 0.25375\ \theta^4)}\ R^{-1} \tag{A.11}$$

4. Modulus of Elasticity

Reference: "Material Manual," TRW Equipment Laboratories, February 1966, Report ER-6756, NAS 9-4884, Fig. 50.

Data Points:

t	Y
0 F	10.71×10^6 lbf/in^2
200	9.90
400	8.50
600	6.15

Polynomial Fit:

Temperature Range: 500 to 1200 R

Equation:

$$Y = (10.71 - 0.63\ \theta - 0.115\ \theta^2 - 0.06\ \theta^3) \times 1.44 \times 10^8\ \text{lbf/ft}^2 \tag{A.12}$$

where

$$\theta = \frac{T - 459.67\ R}{200\ R} \tag{A.13}$$

Maximum Error: 0.38%

III. BERYLLIUM (1/2 - 3% Be O)

1. Specific Heat

Reference: Touloukian, Y. S., "Thermophysical Properties of High Temperature Solid Materials," Thermophysical Properties Research Center, Purdue University, Vol. 6-11, 1967, pp. 753-4.

Data Points:

T	c_p
800 R	0.536 Btu/(lbm R)
1000	0.585
1200	0.622
1400	0.652
1600	0.680

Polynomial Fit:

Temperature Range: 400 to 1700 R

Equation:

$$c_p = (0.536 + 0.05667\ \theta - 0.0085\ \theta^2 + 0.00083\ \theta^3) \times 32.174\ \text{Btu/(slug R)} \quad (A.14)$$

where

$$\theta = \frac{T - 800\ R}{200\ R} \quad (A.15)$$

Maximum Error: 0.88%

2. Thermal Conductivity

Reference: Touloukian, Y. S., "Thermophysical Properties of High Temperature Solid Materials," Thermophysical Properties Research Center, Purdue University, Vol. 6-11, 1967, pp. 757-9.

Data Points:

T	k
400 R	108.863 Btu/(hr ft R)
600	98.944
800	89.751
1000	80.80
1200	72.091

Polynomial Fit:

Temperature Range: 400 to 1700 R

Equation:

$$k = (108.863 - 10.5643\ \theta + 0.82683\ \theta^2 - 0.20167\ \theta^3 + 0.020167\ \theta^4)\ \text{Btu/(hr ft R)} \tag{A.16}$$

where

$$\theta = \frac{T - 400\ \text{R}}{200\ \text{R}} \tag{A.17}$$

Maximum Error: 0.90%

3. Temperature Variation of Thermal Conductivity

Equation A.15 was differentiated with respect to temperature to yield

$$\frac{1}{k}\frac{dk}{dT} =$$

$$\frac{1}{200}\ \frac{(-10.5643 + 1.65367\ \theta - 0.60501\ \theta^2 + 0.080668\ \theta^3)}{(108.863 - 10.5643\ \theta + 0.826830\ \theta^2 - 0.20167\ \theta^3 + 0.020167\ \theta^4)}\ R^{-1} \tag{A.18}$$

4. Modulus of Elasticity

Reference: "Material Manual," TRW Equipment Laboratories, February 1966, Report ER-6756, Contract No. NAS 9-4884, Fig. 51.

Data Points:

t	Y
0 F	44.36×10^6 lbf/in^2
400	40.41
800	33.95
1200	21.80

Polynomial Fit:

Temperature Range: 500 to 1700 R

Equation:

$$Y = (44.36 - 3.755\ \theta + 0.335\ \theta^2 - 0.53\ \theta^3) \times 1.44 \times 10^8\ \text{lbf/ft}^2 \tag{A.19}$$

where

$$\theta = \frac{T - 459.67\ R}{400\ R} \tag{A.20}$$

Maximum Error: 0.28%

APPENDIX B

COOLANT FLUID PROPERTIES

I. HELIUM

1. Equation of State Explicit in Pressure

Reference: Akin, S. W., Trans. ASME, Vol. 72, p. 751, 1950.

This reference was used for all Helium properties and for brevity it is not repeated as the reference for the properties listed below.

Equation: The National Bureau of Standards has published a Bendict-Webb-Rubin equation for helium; this equation was found to be valid only up to the specified pressure limit of 3000 lbf/in^2. Preference was therefore given to the following Beattie-Bridgeman equation:

$$p = \rho^2[RT(1 - \alpha)(\frac{1}{\rho} + B_1) - A] \tag{B.1}$$

where

$$\alpha = \frac{C}{T^3}\rho$$

$$A = A_1(1 - a\rho)$$

The values of the constants in Eq. B.1, in MKSA units, are:

$R = 2.07702 \times 10^3$ Nm/kgk
$A_1 = 1.369595 \times 10^2$ Nm^4/kg^2
$B_1 = 3.5002295 \times 10^{-3}$ m^3/kg
$C = 1.0000658 \times 10^1$ km^3/kg
$a = 1.496103 \times 10^{-2}$ m^3/kg

Temperature Range: 160 to 860 R

Pressure Range: 2116 to 360000 lbf/ft^2

Maximum Error: 0.095%

2. Equation of State Explicit in Density

Since the equation of state is needed explicit in density, Eq. B.1 was solved using Newton-Raphson iteration method along an isotherm to give

$$\rho_{i+1} = \rho_i - \frac{p - p(\rho_i)}{(\partial p/\partial \rho)_T} \tag{B.2}$$

Using Eq. B.1, one obtains

$$\left(\frac{\partial p}{\partial \rho}\right)_T = RT + 2(RB_1T - A_1 - \frac{CR}{T^2})\rho + 3(A_1a - \frac{CRB_1}{T^2})\rho^2 \tag{B.3}$$

3. Isobaric Thermal Expansion Coefficient

The isobaric thermal expansion coefficient is defined by the equation

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \tag{B.4}$$

Since the equation of state (Eq. B.1) is explicit in the pressure, one can write β as:

$$\beta = \frac{1}{\rho}\frac{(\partial p/\partial T)_\rho}{(\partial p/\partial \rho)_T} \tag{B.5}$$

or

$$\beta = \frac{R[\rho + (B_1 + \frac{2C}{T^3})\rho^2 + \frac{2CB_1}{T^3}\rho^3]}{\rho[RT + 2\rho(RB_1T - A_1 - \frac{CR}{T^2}) + 3\rho^2(A_1a - \frac{CRB_1}{T^2})]} \tag{B.6}$$

4. Isothermal Compressibility

The isothermal compressibility is defined by the equation

$$\kappa = \frac{1}{\rho} \left(\frac{\partial \rho}{\partial p}\right)_T \tag{B.7}$$

Making use of Eq. B.3, the isothermal compressibility can be written as

$$\kappa = 1/\rho[RT + 2\rho(RB_1T - A_1 - \frac{CR}{T^2}) + 3\rho^2(A_1a - \frac{CRB_1}{T^2})] \tag{B.8}$$

5. Specific Heat at Constant Pressure:

Equation: Experimental and quantum statistical data for helium show that at zero-pressure, the specific heat at constant volume is independent of temperature

$$c_v^o = \frac{3}{2} R \tag{B.9}$$

Using Maxwell's equations, the following expression is obtained

$$c_v = c_v^o - T\int_{\rho_o}^{\rho} \left(\frac{\partial^2 p}{\partial T^2}\right)_\rho \frac{d\rho'}{(\rho')^2} \tag{B.10}$$

From the equation of state, (Eq. B.1) the integration is carried out in closed form to give

$$c_v = R[\frac{3}{2} + 6a\ (1 + \frac{\rho}{2} B_1)] \tag{B.11}$$

The relation between specific heat at constant pressure and that at constant volume is given by:

$$c_p = c_v + \frac{T\beta^2}{\rho\kappa} \tag{B.12}$$

Temperature Range: 180 to 900 R

Pressure Range: 2116 to 216000 lbf/ft

Maximum Error: 0.58% for cp

6. Enthalpy

The variation of internal energy with both temperature and density is

$$du = c_v dT + [p - T \left(\frac{\partial p}{\partial T}\right)_\rho] \frac{d\rho}{\rho^2} \quad .$$

Substitution of c_v from Eq. B.11 and equation of state data from Eq. B.1 followed by integration along an isochore and an isotherm, one obtains

$$u = u_o + R \left[\frac{3}{2} (T - T_o) + 3 \rho C \left(1 + \frac{B_1}{2}\right)\left(\frac{1}{T_o^2} - \frac{1}{T^2}\right)\right] + \left(\frac{3 R C}{T^2} + A_1\right)$$

$$(\rho_o - \rho) + \frac{1}{2} \left(\frac{3 C R B_1}{T^2} - A_1 a\right)(\rho_o^2 - \rho^2)$$

where $u_o = 3.992 \times 10^4$ j/kg
$T_o = 10.938889$ K
$\rho_o = 4.669193$ kg/m^3
with T in K and u in j/kg.

The enthalpy may then be determined from the equation

$$h = u + \frac{p}{\rho}$$

7. Thermal Conductivity

Data Points:

T	k
160 R	0.0404 Btu/(hr ft R)
360	0.0676
560	0.090
760	0.1094

Polynomial Fit:

Temperature Range: 160 to 860 R

Equation:

$$k = (0.0404 + 0.0302\ \theta - 0.0033\ \theta^2 + 0.0003\ \theta^3)\ \text{Btu/(hr ft R)} \tag{B.13}$$

where

$$\theta = \frac{T - 160\ R}{200\ R}$$

Maximum Error: 0.54%

8. Temperature Variation of Thermal Conductivity

Eq. B. 13 was differentiated with respect to temperature to yield

$$\frac{1}{k}\frac{dk}{dT} = \frac{1}{200}\ \frac{(0.0302 - 0.0066\ \theta + 0.0009\ \theta^2)}{(0.0404 + 0.0302\ \theta - 0.0033\ \theta^2 + 0.0003\ \theta^3)}\ \frac{1}{R} \tag{B.14}$$

9. Dynamic Viscosity

Equation: Viscosity correlations are usually based on the concept of residual viscosity:

$$\psi_1(\rho) = \mu(\rho,T) - \mu^*(T) \tag{B.15}$$

where

ψ_1 is the residual viscosity (function of density alone).

μ^* is the dynamic viscosity at atmospheric pressure.

For helium, the dynamic viscosity is given by:

$$\mu = \mu^* = (2.58394 \times 10^{-5}\ T/°R)^{0.647} \quad \text{slug/(ft hr)} \tag{B.16}$$

Temperature Range: 160 to 660 R

Maximum Error: 0.29%.

II. SILICON OIL

The following properties are for Dow Corning 200 Silicon Oil (1 Centistoke at 77 F).

1. Isothermal Compressibility

Reference: Gunst, S. B., "Density-Pressure Relationships for Two Low-Viscosity Dimethyl Siloxanes," Trans. ASME 72, May 1950, pp. 401-7.

Data Points: Variation of κ with temperature at 0 psig and 500 psig are given below:

t	κ_o	κ^o_{500}
100 F	12.35×10^{-6} in^2/lbf	11.60×10^{-6} in^2/lbf
150	16.05	14.94
200	20.45	18.82
250	26.25	23.86
300	36.55	31.88

Polynomial Fit:

Temperature Range: 560 to 760 R

Pressure Range: 2116 to 74116 lbf/ft^2

Equation: The variation of κ_o with temperature at 0 psig is given by

$$\kappa_o = (12.35 + 2.9833\,\theta + 1.1\,\theta^2 - 0.48333\,\theta^3 + 0.1\,\theta^4) \times 10^{-6} \text{ in}^2/\text{lbf} \tag{B.17}$$

where
$$\theta = \frac{T - 559.67 \text{ R}}{50 \text{ R}} \tag{B.17a}$$

κ is assumed to vary linearly on the above range of pressure, hence

$$\kappa = a + b\, p \tag{B.18}$$

where

$$a = \kappa_o$$

(B.18a)

$$b = \left(\frac{\partial \kappa}{\partial p}\right)_T \simeq \frac{\kappa_{500} - \kappa_o}{500 \text{ psi}}$$

and p is the pressure in psig and κ is in in^2/lbf

Fitting a power polynomial through $\left(\frac{\partial \kappa}{\partial p}\right)_T$ with the same values for temperature as indicated in the table results in the equation

$$b = (-1.5 - 0.0133\,\theta - 1.18\,\theta^2 + 0.57333\,\theta^3 - 0.1\,\theta^4) \times 10^{-9} \quad in^4/lbf^2 \tag{B.19}$$

where θ is given in Eq. B.17a.

Maximum Error: There was no difference between the computed and the input data within the accuracy of the computation.

2. Equation of State Explicit in Density

Reference: Gunst, S. B., "Density-Pressure Relationships for Two Low-Viscosity Dimethyl Siloxanes, "Trans. ASME, May 1950, pp. 401-7.

Data Points: Values for the variation of density with temperature at 0 psig are given below:

t	ρ_o
150 F	0.7767 gm/cm^3
200	0.7479
250	0.7188
300	0.6900

Polynomial Fit:

Temperature Range: 540 to 760 R

Pressure Range: 2116 to 146116 lbf/ft^2

Equation:

$$\rho_o = (0.7767 - 0.0288\ \theta) \times 1.94 \quad slug/ft^3 \tag{B.20}$$

where

$$\theta = \frac{T - 609.67\ R}{50\ R} \tag{B.20a}$$

The variation of density with pressure is given by

$$dz = \frac{d\rho}{\rho} = -\ \beta\ dT + \kappa\ dp \tag{B.21}$$

Integration along the isotherm T_o = 609.67 R and from p' = 0 psig to $p' = p$, using Eq. B.18 results in

$$z(p,T_o) = a(T_o)p + b(T_o)\ \frac{p^2}{2}$$

Integration along the isobar p, from $T' = T_o$, to $T' = T$, using Eq. B.25, yields

$$z(p,T)-z(p,T_o) = p\int_{T_o}^{T} a'(T')dT' + \frac{p^2}{2}\int_{T_o}^{T} b'(T')dT' - \int_{T_o}^{T} c(T')dT'$$

which after simplification reduces to

$$\rho = \rho_o\ e^{ap + \frac{1}{2} b\ p^2} \tag{B.22}$$

where values for a and b are given in Eq. B.18a.

Maximum Error: 0.128%

3. Equation of State Explicit in Pressure

Since the equation of state is needed explicit in pressure, Eq. B.22 was rearranged to yield

$$p = \frac{1}{b}\left[-a + \sqrt{a^2 + 2b\ln\frac{\rho}{\rho_o}}\right] \qquad (B.23)$$

4. Isobaric Thermal Expansion Coefficient

The zero-pressure isobaric thermal expansion coefficient can be written as:

$$\beta_o = \frac{1}{\rho_o}\left(\frac{\partial \rho_o}{\partial T}\right)_p$$

where ρ_o is given by Eq. B.20.

or

$$\beta_o = \frac{0.0288}{50(0.7767 - 0.0288\ \theta)} \quad \frac{1}{R} \qquad (B.24)$$

where θ is given by Eq. B.20a.

Making use of Eq. B.21, together with the principle of an exact differential, one may write

$$\left(\frac{\partial \beta}{\partial p}\right)_T = -\left(\frac{\partial \kappa}{\partial T}\right)_p$$

From Eq. B.18, the variation of β with both pressure and temperature is given by

$$\beta = \beta_o - a'\ p - \frac{b'^2}{2}\ p^2 \qquad (B.25)$$

where the prime superscript indicates differentiation with respect to temperature. The expressions for a and b as a function of temperature are given in Eqs. B.17 and 19, respectively.

5. Specific Heat at Constant Pressure

Reference: Dow Corning, Bulletin 05-145, February 1966.

Data Points: The available data for the variation of zero pressure specific heat at constant pressure for 2 centistokes are:

t	c_p^o	
80 F	0.448	Btu/(lbm F)
160	0,454	
240	0.463	
320	0.476	
400	0.491	

Polynomial Fit:

Temperature Range: 540 to 860 R

Pressure Range: 2116 to 74116 lbf/ft^2

Equation: The above data for 2 centistokes silicon oil were multiplied by the ratio of c_p^o for 1 centistoke to 2 centistokes at 77°F, to give the following expression for the zero-pressure specific heat at constant pressure for 1 centistoke silicon oil

$$c_p^o = (0.46 + 0.00471\,\theta + 0.00141\,\theta^2 + 0.000043\,\theta^3) \times 32.174 \text{ Btu/(slug R)} \tag{B.26}$$

where

$$\theta = \frac{T - 539.67 \text{ R}}{80 \text{ R}} \tag{B.26a}$$

The variation of c_p with pressure is given by

$$c_p = c_p^o - T \int_{\rho_o}^{\rho} \left(\frac{\partial^2}{\partial T^2}\right)_p \left(\frac{1}{\rho}\right) dp' \tag{B.27}$$

Since the exponent in Eq. B.22 is small, the equation for the density, when expanded in a power series, may be truncated after the second term in the expansion. Applying Eq. B.27 to the two-term expression for density as a function of pressure and temperature by integrating along an isotherm T from $p' = 0$ psig to $p' = p$, results in the expression for

$$c_p = c_p{}^\circ - \frac{TI}{\rho_o} \tag{B.28}$$

where

$$I = z_1 p + z_2 p^2 + z_3 p^3 + z_4 p^4 + z_5 p^5$$

and

$$z_1 = 2\left(\frac{\rho_o'}{\rho_o}\right)^2$$

$$z_2 = \frac{1}{2}\left[\left(2\,\frac{\rho_o'}{\rho_o}\,a' - a''\right) - az_1\right]$$

$$z_3 = \frac{1}{3}\left[a'^2 - \frac{b''}{2} + \frac{\rho_o'}{\rho_o}\,b'\right) - a\left(2\,\frac{\rho_o'}{\rho_o}\,a' - a''\right) + \frac{1}{2}(a^2 - b)z_1\right]$$

$$z_4 = \frac{1}{4}\left[a'b' - a\left(a'^2 - \frac{b''}{2} + \frac{\rho_o'}{\rho_o}\,a'\right) + \frac{1}{2}(a^2 - b)\left(2\,\frac{\rho_o'}{\rho_o}\,a' - a''\right)\right.$$
$$\left. + \frac{1}{2}\,abz_1\right]$$

$$z_5 = \frac{1}{10}\left[\frac{b'^2}{2} - 2a\,a'b' + (a^2 - b)\left(a'^2 - \frac{b''}{2} + \frac{\rho_o' b'}{\rho_o}\right)\right.$$
$$\left. + ab\left(2\,\frac{\rho_o'}{\rho_o}\,a' - a''\right) + \frac{1}{2}\,b^2\,z_1\right]$$

where the prime superscript indicates differentiation with respect to temperature. The symbol a represents the zero pressure isothermal compressibility defined in equation B.17 and b is defined by equation B.19.

Maximum Error: For zero pressure specific heat at constant pressure the maximum error was 0.065%. For higher pressures no experimental data were available for comparison. However, the expression for enthalpy was numerically differentiated with respect to temperature at constant pressure and compared with the computed values of specific heat at constant pressure. The comparison showed no difference within the accuracy of the computation.

6. Enthalpy

The variation of enthalpy with both pressure and temperature is given by:

$$dh = c_p^o \, dT + \frac{1}{\rho} [1 - T\beta] \, dp$$

This expression was integrated along the isobar p = 0 psig from T' = 539.65 R to T' = T, and then along an isotherm T from p' = 0 psig to p = p, to give

$$\begin{aligned} h = \ & \{ 80(0.46 + 0.00471\,\theta + 0.00141\,\theta^2 + 0.000043\,\theta^3) \\ & + \frac{1}{\rho_o \cdot 337.37} [- \frac{1}{20} b\, b'\, T\, p^5 - \frac{1}{8} (a\, b' + a'\, b)\, Tp^4 \\ & + \frac{1}{6} (T(b' - a\, a') - b(1 + T\, \frac{\rho_o'}{\rho_o}))p^3 + \frac{1}{2} (a'\, T - a\, (1 \\ & + T\, \frac{\rho_o'}{\rho_o}))\, p^2 + (1 + T\, \frac{\rho_o'}{\rho_o})\, p] \times 32.174 \} \quad \text{Btu/slug} \end{aligned} \qquad (B.29)$$

where
θ is given by Eq. B.26a
T is temperature in R
a is given by Eq. B.17 in in^2/lbf
ρ_o is given by Eq. B.20 in $slug/ft^3$
b is given by Eq. B.19 in in^4/lbf^2
p is pressure in lbf/in^2
and primes denote differentiation with temperature.

7. Dynamic Viscosity

Reference: Dow Corning, Bulletin 05-153, July 1966.

Data Points:

t	ν	
0 F	1.98	centistokes
100	0.874	
200	0.56	
300	0.41	

Polynomial Fit:

Temperature range: 460 to 760 R

Equation:

$$\ln \nu = (0.683 - 1.0845\ \theta + 0.3065\ \theta^2 - 0.04\ \theta^3) \tag{B.30}$$

where $\theta = \dfrac{T - 459.67\ R}{100.0\ R}$

where ν is in centistokes and the dynamic viscosity is given by

$$\mu = \nu\ \rho \tag{B.31}$$

Maximum Error: 0.77%

8. Thermal Conductivity

Reference: Dow Corning, Bulletin 05-145, February 1966.

Data Points: The available data for the variation of thermal conductivity with temperature for 2 centistokes are:

t	k	
- 100 F	0.0674	Btu/(hr ft F)
100	0.0626	
300	0.0578	

Polynomial Fit:

Temperature Range: 360 to 860 R

Equation: The procedure that was used for specific heat at constant pressure was followed to get an expression for the variation of thermal conductivity with temperature for 1 centistoke silicon oil. The resulting expression for the thermal conductivity is given by

$$k = (7.0052 - 2.2105 \times 10^{-3} T/R) \times 10^{-2} \text{ Btu/(hr ft R)} \qquad (B.32)$$

Maximum Error: There was no difference between the computed and the input data within the accuracy of the computation.

9. Temperature Variation of Thermal Conductivity

Eq. B.32 was differentiated with respect to temperature to yield

$$\frac{1}{k}\frac{dk}{dT} = \frac{-2.2105 \times 10^{-3}}{7.0052 - 2.2105 \times 10^{-3} T/^{\circ}R)} \ 1/R \qquad (B.33)$$

III NAK - (78.6% K)

The following physical properties of NaK(78.6 wt% K) were extracted from the latest version of the "Liquid Metals Handbook, Sodium and NaK Supplement" (to be published). Some typical properties of NaK are:

Melting Point: 92 F

Boiling Point: 1445 F

Surface Tension: 0.00739 lbf/ft at Melting point

Since all property values were taken from this single reference, the reference is omitted in each section below.

1. Equation of State Explicit in Density

Data Points: Values for the variation of density with temperature at zero pressure are given by

t	ρ_o
200 F	53.21 lbm/ft^3
500	50.68
800	48.15
1100	45.62
1400	43.09

Polynomial Fit:

Temperature Range: 660 to 1860 R

Equation:

$$\rho_o = (58.773064 - 0.008433\ T/R)/32.174\ slug/ft^3 \tag{B.34}$$

Since the isothermal compressibility for NaK is assumed to be independent of pressure, Eq. B22 reduces to

$$\rho = \rho_o\, e^{\kappa p} \tag{B.35}$$

where p is the gage pressure. Since the exponent is small, the power series expansion for Eq. B.35 may be truncated after the second term and the variation of density with both pressure and temperature is given by

$$\rho = \rho_o (1 + \kappa p) \tag{B.36}$$

An expression for κ is given later in this section.

Maximum Error: At zero pressure, there was no difference between the computed and the input data, within the accuracy of the computation. For higher pressures there were no experimental data available for comparison.

2. Equation of State Explicit in Pressure

Since the equation of state is needed explicit in pressure, Eq. B.36 was rearranged to yield

$$p = \frac{1}{\kappa} \left(\frac{\rho}{\rho_o} - 1\right) \tag{B.37}$$

3. Isobaric Thermal Expansion Coefficient

The isobaric thermal expansion coefficient is defined in Eq. B.4. From Eq. B.34, the zero pressure isobaric thermal expansion coefficient is given by:

$$\beta_o = \frac{0.008433}{(58.773064 - 0.008433TR^{-1})} \frac{1}{R} \tag{B.38}$$

Due to the lack of experimental data, the isobaric thermal expansion coefficient was assumed to be independent of pressure.

4. Isothermal Compressibility

In view of the experimental difficulties associated with the measurement of isothermal compressibility at elevated temperatures, such data are not generally available for liquid metals. However, the well-known relationship between velocity of sound c, density ρ, and isentropic compressibility κ_s is

$$\kappa_s = \frac{1}{\rho c^2} \tag{B.39}$$

which makes an alternative approach to the problem possible, if velocities of sound can be measured. Under these circumstances the isothermal compressibility may be obtained from the relation

$$\kappa = \gamma \kappa_s \tag{B.40}$$

where

$$\gamma = \frac{c_p}{c_v}$$

The relation between c_p and c_v is given by

$$c_p - c_v = \frac{T\beta^2}{\rho\kappa} \tag{B.41}$$

From Eqs. B.40 and B.41, one gets

$$\kappa = \kappa_s + \frac{T\beta^2}{\rho c_p}$$

or

$$\kappa_o = \left\{ \frac{1}{\rho} \left[\frac{1}{c^2} + \frac{T\beta^2}{c_p} \right] \right\}_{\substack{T_o \\ P_o}} \tag{B.42}$$

Due to the lack of experimental data Eq. B.42 was evaluated at the absolute pressure p_o of one atmosphere and the temperature of T_o = 1260 R.

at T_o = 1260 R

$$\rho_o = 48.15 \text{ lbm/ft}^3$$

$$c_o = 7544 \text{ ft/sec}$$

$$\beta_o = 1.75149 \times 10^{-4} \text{ 1/R}$$

$$C_{p,o} = 0.2091 \text{ Btu/(lbm R)}$$

5. Specific Heat at Constant Pressure

Data Points: For zero-pressure specific heat at constant pressure are given by:

t	c_p^o
200 F	0.2255 Btu/(lbm F)
500	0.1239
800	0.2093
1100	0.2091
1400	0.2120

Polynomial Fit:

Temperature Range: 660 to 1860 R

Equation:

$$c_p^o = (0.2255 - 0.016292\ \theta + 0.00539\ \theta^2 - 0.000758\ \theta^3 + 0.000054\ \theta^4) \times 32.174 \text{ Btu/(slug R)} \tag{B.44}$$

where

$$\theta = \frac{T - 659.67\ R}{300\ R} \tag{B.44a}$$

The variation of c_p with pressure is given by

$${}_p = c_p^o - T \int_{p_o}^{p} \frac{\partial^2}{\partial T^2} \left(\frac{1}{\rho}\right)_p dp'$$

Integrating along the isotherm T from p = 0 psig to p' = p, using Eqs. B.36 and B.38 results in

$$c_p = c_p^o - \frac{2T\beta_o^2}{\rho_o \kappa} \ln (1 + \kappa p) \tag{B.45}$$

Maximum Error: At zero pressure, the maximum error was 0.075%.

6. Enthalpy

The variation of enthalpy with both pressure and temperature is given by

$$dh = c_p\ dT + \frac{1}{\rho} [1 - T\beta]\ dp$$

The enthalpy was arbitrarily chosen to be zero near the melting point, or $T = 469.67^\circ R$. The above expression was integrated along an isobar p = 0 psig from $T' = 469.67^\circ R$ to T' = T, and then along an isotherm T from p' = 0 psig to p' = p, to give

$$h = [300\ (0.2255\ \theta - 0.016292 \frac{\theta^2}{2} + 0.00539 \frac{\theta^3}{3} - 0.000758 \frac{\theta^4}{4} + 0.000054 \frac{\theta^5}{5}) + \frac{1 - T\beta}{\rho_o \kappa} \ln (1 + \kappa \rho) \times \frac{1}{778.26}]\ 32.174\ \text{Btu/slug} \tag{B.46}$$

where ρ and ρ_o are in lbm/ft^3, κ is in ft^2/lbf T_o in R, θ is given in Eq. B.44a, β is in R^{-1} and p is gage pressure in lbf/ft^2.

7. Thermal Conductivity

Data Points:

t	k
200 F	13.36 Btu/(hr ft F)
500	14.57
800	15.18
1100	15.03
1400	14.13

Polynomial Fit:

Temperature Range: 660 to 1860 R

Equation:

$$k = (13.36 + 1.414167\ \theta - 0.142083\ \theta^2 - 0.069167\ \theta^3 + 0.007083\ \theta^4)\ \text{Btu/(hr ft R)} \tag{B.47}$$

where

$$\theta = \frac{T - 659.67\ R}{300\ R}$$

Maximum Error: 0.2%

8. Temperature Variation of Thermal Conductivity:

Eq. B.47 was differentiated with respect to temperature to yield

$$\frac{1}{k}\frac{dk}{dT} = \frac{1}{300}\ \frac{(1.414167 - 0.284166\theta - 0.207501\theta^2 + 0.028332\theta^3}{(13.36 + 1.414167\theta - 0.142083\theta^2 - 0.069167\theta^3 + 0.007083\theta^4)}\ \frac{1}{R} \tag{B.48}$$

9. Dynamic Viscosity

Data Points:

t	μ
200 F	1.1316 lbm/(ft hr)
500	0.746
800	0.534
1100	0.411
1400	0.340

Polynomial Fit:

Temperature Range: 660 to 1860 R

Equation:

$$\mu = (1.316 - 0.896667\ \theta + 0.419833\ \theta^2 - 0.102833\ \theta^3 + 0.009667\ \theta^4)/32.174 \qquad \text{slug/(ft hr)} \tag{B.49}$$

where

$$\theta = \frac{T - 659.67R}{300R}$$

Maximum Error: 1.2%

IV. FC-75 INERT FLUOROCHEMICAL LIQUID

The thermodynamic and transport properties of FC-75 fluid are extracted from "3M Brand Inert Fluorochemical Liquids, 3M Company, Chemical Division, 1965."

Due to the lack of experimental data, all properties were evaluated at atmospheric pressure and were assumed to be pressure independent.

At one atmosphere some typical properties are:

Nominal Boiling Point:	216 F
Pour Point:	- 135 F
Surface Tension, at 77F:	15 dynes/cm

1. Equation of State

Data Points:

t	ρ	
- 50 F	120.7	lbm/ft^3
70	110.5	
190	100.3	

Polynomial Fit:

Temperature Range: - 80 to 216 F

Equation:

$$\rho = (155.522 - 0.085\ T\ R^{-1}) \times 32.174\ slug/ft^3 \qquad \text{(B.50)}$$

Maximum Error: There was no difference between the computed and input data, within the accuracy of computation.

2. Isobaric Thermal Expansion Coefficient

Using the definition of the isobaric thermal expansion coefficient, Eq. B.4, and Eq. B.50, one obtains

$$\beta = \frac{0.085}{155.522 - 0.085\ T\ R^{-1}} \quad \frac{1}{R} \tag{B.51}$$

3. Isothermal Compressibility

Since the equation of state (Eq. B.50) was assumed to be pressure independent, the isothermal compressibility defined by Eq. B.7 was assigned the value of zero

$$\kappa \equiv 0$$

4. Specific Heat at Constant Pressure

Data Points: The variation of the zero pressure specific heat at constant pressure is given by:

t	c_p^o	
80^o F	0.2464	Btu/(lbm F)
140	0.2610	
200	0.2756	

Polynomial Fit:

Temperature Range: 70 to 210 F

Equation:

$$c_p^o = (0.115082 + 2.4333 \times 10^{-4}\ T\ R^{-1}) \times 32.174 \quad \text{Btu/(slug R)} \tag{B.52}$$

The variation of c_p with pressure is given by Eq. B.27. With ρ independent of pressure, Eq. B.27 was integrated along an isotherm T from p' = 0 psig to p' = p resulting in:

$$c_p = c_p^o - \frac{2\beta^2 T}{\rho} p \tag{B.53}$$

A check on the magnitude of the terms in Eq. B.53, using typical running conditions, showed that the term $2\beta^2 TP/\rho$ was only 0.00064% of c_p. Therefore, c_p was taken to be a function of temperature alone, namely

$$c_p = c_p^o \tag{B.54}$$

Maximum Error: 0.025%

5. Enthalpy

The variation of enthalpy with both pressure and temperature is given by

$$dh = c_p^o \, dT + \frac{1}{\rho} (1 - T\beta) \, dp \tag{B.55}$$

This expression was integrated along the isobar p = 0 psig from T' = T = 324.67 R to T' = T, and then along an isotherm T from p' = 0 psig to p' = p to give

$$h = [0.115082 \; (T - T_o) + \frac{1}{2} \times 2.4333 \times 10^{-4} \; (T^2 - T_o^2)] \times 32.174 + \frac{p}{778.26 \; \rho} (1 - T \; \beta) \text{ Btu/slug} \tag{B.56}$$

where ρ is in slug/ft^3, p is gage pressure in lbf/ft^2, T is in R and β is in R^{-1}.

A check of the magnitude of the terms in Eq. B.56, using typical running conditions, showed that the last term which accounts for the pressure variation is only 0.00087% of h. Hence the enthalpy was taken to be a function of temperature alone, or

$$h = [0.115082\ (T - T_o) + \frac{1}{2} \times 2.4333 \times 10^{-4} (T^2 - T_o^2)] \times 32.174 \quad \text{Btu/slug} \tag{B.57}$$

Maximum Error: No data for enthalpy at atmospheric pressure were available for comparison. However, when the value of c_p (Eq. B.52) was compared with the result of differentiation of h with respect to temperature, there was no difference within the accuracy of the computation.

6. Thermal Conductivity

Data Points:

t	k	
- 50 F	0.08745	Btu/(hr ft F)
50	0.0809	
150	0.0744	

Polynomial Fit:

Temperature Range: - 100 to 216 F

Equation:

$$k = 0.114181 - 6.53 \times 10^{-3}\ T\ R^{-1} \quad \text{Btu/(hr ft F)} \tag{B.58}$$

Maximum Error: 0.044%

7. Dynamic Viscosity

Data Points: The variation of kinematic viscosity with temperature is given by:

t	ν	
-50 F	5.15	centistokes
10	1.74	
70	0.84	
130	0.50	

Polynomial Fit:

Temperature Range: -80 to 190 F

Equation:

$$\nu = e\ (1.639 - 1.312933\ \theta + 0.25265\ \theta^2 - 0.02471667\ \theta^3) \text{ centistokes} \tag{B.59}$$

where

$$\theta = \frac{T - 409.67 \text{ R}}{60 \text{ R}}$$

The dynamic viscosity is given by

$$\mu = \nu\rho \tag{B.60}$$

Maximum Error: 0.82%

V. FC-43 INERT FLUROCHEMICAL LIQUID

The thermodynamic and transport properties of the FC-43 are extracted from "3M Brand Inert Fluorochemical Liquids, 3M Company, Chemical Division, 1965."

Due to the lack of experimental data, all properties were evaluated at atmospheric pressure and were assumed to be pressure independent.

At one atmosphere some typical properties are:

Nominal Boiling Point:	345 F
Pour Point:	- 58 F
Surface Tension at 77F:	16 dynes/cm

1. Equation of State

Data Points:

t	ρ	
- 20 F	123.6	lbm/ft^3
130	112.15	
280	100.75	

Polynomial Fit:

Temperature Range: - 50 to 340 F

Equation:

$$\rho = (157.0883 - 0.076167\ T\ R^{-1}) \times 32.174\ \text{slug/ft}^3 \qquad \text{(B.61)}$$

Maximum Error: There was no difference between the computed and input data, within the accuracy of computation.

2. Isobaric Thermal Expansion Coefficient

Using the definition of the isobaric thermal expansion coefficient, Eq. B.4, and Eq. B.61, one obtains

$$\beta = \frac{0.076167}{157.0883 - 0.076167 \ T \ R^{-1}} \ \frac{1}{R} \tag{B.62}$$

3. Isothermal Compressibility

Since the equation of state (Eq. B.61) was assumed to be pressure independent, the isothermal compressibility defined by Eq. B.7 was assigned the value of zero.

$$\kappa \equiv 0$$

4. Specific Heat at Constant Pressure

Data Points: The variation of zero pressure specific heat at constant pressure is given by:

t	c_p^o
40 F	0.25 Btu/(lbm F)
77	0.27

Polynomial Fit:

Temperature Range: 40 to 77 F

Equation:

$$c_p^o = (-0.020092 + 5.4054 \times 10^{-4} \ T \ R^{-1}) \times 32.174$$

$$\text{Btu/(slug R)} \tag{B.63}$$

A similar procedure to that used in the case of FC-75 (See Section B IV 4) has shown that to a close approximation c_p is pressure independent, or

$$c_p = c_p^o \tag{B.64}$$

Maximum Error: There was no difference between the computed and input data within the accuracy of computation.

5. Enthalpy

The variation of enthalpy with both pressure and temperature is given by Eq. B.55. Integration of this equation in a procedure similar to that followed for the coolant fluid FC-75 yields

$$h = [-0.020092 \ (T - T_o) + \frac{1}{2} \times 5.4054 \times 10^{-4}(T^2 - T_o^2)] \times$$

$$32.174 + \frac{p}{778.26\rho} (1 - T\beta) \text{ Btu/slug} \tag{B.65}$$

where T_o = 401.67 R, ρ is in slug/ft^3, T is in R, β is in R^{-1}, and p is gage pressure in lbf/ft^2.

A check of the magnitude of the terms in Eq. B.64, using typical running conditions, showed that the last term which accounts for the pressure variation is only 0.00084% of h. Therefore the enthalpy was taken to be a function of temperature alone or

$$h = [-0.020092 \ (T - T_o) + \frac{1}{2} \times 5.4054 \times 10^{-4}(T^2 - T_o^2)] \times$$

$$32.174 \text{ Btu/slug} \tag{B.66}$$

Maximum Error: No data for enthalpy at atmospheric pressure were available for comparison. However, when the value of c_p (Eq. B.63) was compared with the result of differentiation of h with respect to temperature, there was no difference within the accuracy of the computations.

6. Thermal Conductivity

Data Points:

t	k	
- 50 F	0.0512	Btu/(hr ft F)
50	0.0487	
150	0.0462	

Polynomial Fit:

Temperature Range: - 58 to 250 F

Equation:

$$k = 0.061442 - 2.5 \times 10^{-5}\ T\ R^{-1}\ \text{Btu/(hr ft F)} \qquad \text{(B.67)}$$

Maximum Error: 0.11%

7. Dynamic Viscosity

Data Points: The variation of kinematic viscosity with temperature is given by:

t	ν	
- 20 F	15.80	centistokes
70	2.84	
160	0.855	
250	0.35	

Polynomial Fit:

Temperature Range: - 80 to 320 F

Equation:

$$\nu = e \; (2.76 - 2.043483\ \theta + 0.362\ \theta^2$$

$$- 0.034717\ \theta^3) \text{ centistokes} \qquad \text{(B.68)}$$

where

$$\theta = \frac{T - 439.67\ R}{90\ R}$$

The dynamic viscosity is given by

$$\mu = \nu\ \rho \qquad \text{(B.69)}$$

Maximum Error: 1.0%

APPENDIX C

Optical Properties

Three optical properties are required in the radiative analysis discussed in Chapter 6, namely the total hemispherical emittance

$$\varepsilon(T) = \frac{1}{E_b(T)} \int_o^\infty \varepsilon_\lambda\ (T)\ E_{b,\lambda}\ (T) d\lambda \tag{C.1}$$

and the two auxiliary functions (see Eqs. 6.10 and 6.11)

$$XX(T_1, T_2) = \frac{}{E_b(T_2)} \int_o^\infty \varepsilon_\lambda(T_1)\ \varepsilon_\lambda(T_2)\ E_{b,\lambda}\ (T_2) d\lambda \tag{C.2}$$

$$XXX(T_1, T_2, T_3) = \frac{1}{E_b(T_3)} \int_o^\infty \varepsilon_\lambda(T_1)\ \varepsilon_\lambda(T_2)\ \varepsilon_\lambda(T_3)\ E_{b,\lambda}\ (T_3)\ d\lambda \tag{C.3}$$

In view of the temperature independence of the spectral emittance for dielectrics, the two functions XX and XXX are functions of a single temperature, the temperature of the surface element represented by the last subscript on the lef-hand sides of Eqs. 6.10 and 6.11:

$$XX(T) = \frac{1}{E_b(T)} \int_o^\infty \varepsilon_\lambda^{\ 2}\ E_{b,\lambda}\ (T) d\lambda \tag{C.4}$$

$$XXX(T) = \frac{1}{E_b(T)} \int_o^\infty \varepsilon_\lambda^{\ 3}\ E_{b,\lambda}\ (T) d\lambda \tag{C.5}$$

I. SURFACE COATING Z-93

The functions C.1, C.4 and C.5 of the previous section are evaluated for the zinc oxide/potassium silicate coating Z-93 on the basis of spectral reflectance data measured by IITRI and published in the NASA Contractor Report No. 1420, titled Emissivity Coatings for Low-Temperature Space Radiators, by G. R. Cunnington, J. R. Grammer, and F. J. Smith, Lockheed Aircraft Corp., Sunnyvale, Calif., Sept. 1969, pp. 66 through 81.

The evaluated functions defined through Eqs. C.1, 4 and 5 are collocated by power polynomials of this form

$$f(T) = \sum_{i=0}^{N} a_i T^i \qquad \text{(C.6)}$$

For the total hemispherical emittance, a fourth degree power polynomial was found to be satisfactory with

$$\begin{aligned} a_0 &= 0.8990103 \\ a_1 &= -0.1400633 \times 10^{-3} \\ a_2 &= 0.387900 \times 10^{-6} \\ a_3 &= -0.3937509 \times 10^{-9} \\ a_4 &= 0.1015627 \times 10^{-12} \end{aligned}$$

For the auxiliary functions XX and XXX the coefficients are

	XX	XXX
a_0 =	0.7804112	0.6538383
a_1 =	$-0.5527205 \times 10^{-4}$	0.1144374×10^{-3}
a_2 =	0.2530228×10^{-6}	$-0.2432286 \times 10^{-7}$
a_3 =	$-0.3229181 \times 10^{-9}$	$-0.1437500 \times 10^{-9}$
a_4 =	$0.8854202 \times 10^{-13}$	$0.4947915 \times 10^{-13}$

APPENDIX D

I. The Fin-To-Tube Shape Factor

A closed-form integration for the view factor of the fin with respec to the tube was carried out by Mr. Yao. This view factor occurs in Eqs. 6.15 and 6.16. Only the final results are given here.

The reader should recognize that some of the symbols defined below (Eqs. D.1 through 6) apply only here.

Let (x_f, y_f, z_f) designate the position of the center of an area element A_f on the fin and z_m the same on the tube. Let r_e, s_t and s_r represen respectively, the outer tube radius, the fin tip and the fin root thickness, and let the fin height be given as H.

Then, with

$$\rho = x_f^2 + y_f^2 \tag{D.1}$$

$$\beta = \text{arc tg} \frac{y_f}{x_f} \tag{D.2}$$

$$\alpha = \text{arc tg} \frac{s_r - s_t}{2r_c} \tag{D.3}$$

$$\phi = \text{arc tg} \frac{s_r}{2r_e} \tag{D.4}$$

$$a = \rho^2 + r_e^2 + (z_f - z_m)^2 \tag{D.5}$$

$$\phi^* = \text{arc sin} \frac{r_e}{\rho} \tag{D.6}$$

one obtains first

$$Z_1 = \ln \frac{a-2r_e \rho \cos(\phi^*-\beta)}{a-2r_e \rho \cos(\phi-\beta)} + \frac{a-2r_e^2 \cos(\alpha+\beta)}{a-2r_e \rho \cos(\phi^*-\beta)} - \frac{a-2r_e^2 \cos(\alpha+\beta)}{a-2r_e \rho \cos(\phi-\beta)} \tag{D.7}$$

$$Z_2 = \frac{8r_e^2 \rho^2 (z_t-z_m)^2 + 4\rho^2 r_e^2 a-a^3}{2(a^2-4r_e^2\rho^2)^{3/2}} \tag{D.8}$$

$$Z_3 = \arcsin \frac{2r_e\rho-a \cos(\phi^*-\beta)}{a-2r_e\rho \cos(\phi^*-\beta)} - \arcsin \frac{2r_e\rho-a \cos(\phi-\beta)}{a-2r_e\rho \cos(\phi-\beta)} \tag{D.9}$$

$$Z_4 = \frac{2a(z_f-z_m)^2 - a^2 + 4r_e^2\rho^2}{a^2 - 4r_e^2\rho^2} \tag{D.10}$$

$$Z_5 = \frac{r_e \rho \sin(\phi^*-\beta)}{a-2r_e\rho \cos(\phi^*-\beta)} - \frac{r_e \rho \sin(\phi-\beta)}{a-2r_e\rho \cos(\phi-\beta)} \tag{D.11}$$

The final result is

$$SS = \Delta A_1 \Delta z \quad \frac{-Z_1}{4\pi\rho} + \frac{\sin(\alpha+\beta)}{2\pi\rho} \quad \frac{\phi^*-\phi}{2} + Z_2 Z_3 Z_4 Z_5 \tag{D.12}$$

This expression contains all the geometric relations that are required for fin-channel radiative interaction. It needs to be evaluated only once for every fin element.

The values of SS given by Eq. D-12 vary greatly depending on the fin and tube elements under consideration. Typically the shape factor between tube element and adjacent fin element is three to five orders of magnitudes larger than the shape factor between tube element and the next closest fin element. If this large variation in shape factor is allowed to remain, unrealistic oscillations in the fin radiosity will occur and sizeable truncati errors will result when the radiant fluxes are integrated across the fin surface.

To eliminate these truncation errors the local shape factor for the root fin element is replaced by a mean valve between two adjacent elements which have the same Z location. The mean value for the shape factor between a tube element and its adjacent fin element is calculated from

$$SS = \left[\frac{1-\sin}{\pi}\gamma\right]\left[\phi_o + \frac{\sin 2\phi_o}{2}\right] \tag{D.13}$$

rather than Eq. D.12.

Expressions for γ and ϕ_o are:

$$\gamma = \tan^{-1}\left[\frac{Zm - Z_f}{X_f}\right]$$

$$\frac{r_e\,[\cos\phi_o + \tan\phi_o \sin\phi_o] - y_f}{r_e + X_f} - \tan\phi_o = o$$

II. Tube to Tube Shape Factor

The simplified analysis has indicated that optimum dimensions of the radiator system will result in close tube spacing. Therefore for the case of an optiminually designed system, the radiant interaction between adjacent tubes must be taken into account. This section summarizes the results of the shape factor between two fin elements. The procedure used is Hottel's crossed string method which is valid for infinitely long elements that are generated by a straight line moving parallel to itself. The finite length of the tube elements to accounted for by multiplying Hottel's result by a weighting factor.

From Hottel's crossed string method (see Fig. 5) the shape factor between two infinitely long tubes is:

$$F_{1-2} = \left[\frac{1}{\pi/2 - \phi}\right]\left\{ \gamma + \left[\left(\frac{t}{R_2}\right)^2 + \left(\frac{2L}{R_2} - \cos\phi\right)^2 - 1\right]^{1/2} - \left(\frac{2L}{R_2} - \cos\phi\right)\right\} \quad (D.14)$$

where

$$\phi = \sin^{-1}\left(\frac{t}{R_2}\right)$$

t = one half the fin thickness at its root.

R_2 = outside radius of the tube

L = one-half the distance between tube centers

$$\gamma = \frac{\pi}{2} - (\theta_1 + \phi_1)$$

$$\phi_1 = \tan^{-1}\left(\frac{t}{2L - R_2\cos\phi}\right)$$

$$\theta_1 = \cos^{-1}\left(\frac{R_2 \sin\phi_1}{t}\right)$$

The weighting factor for two tube elements of width ΔZ located at Z_1, Z_2 (see Fig. 5) is

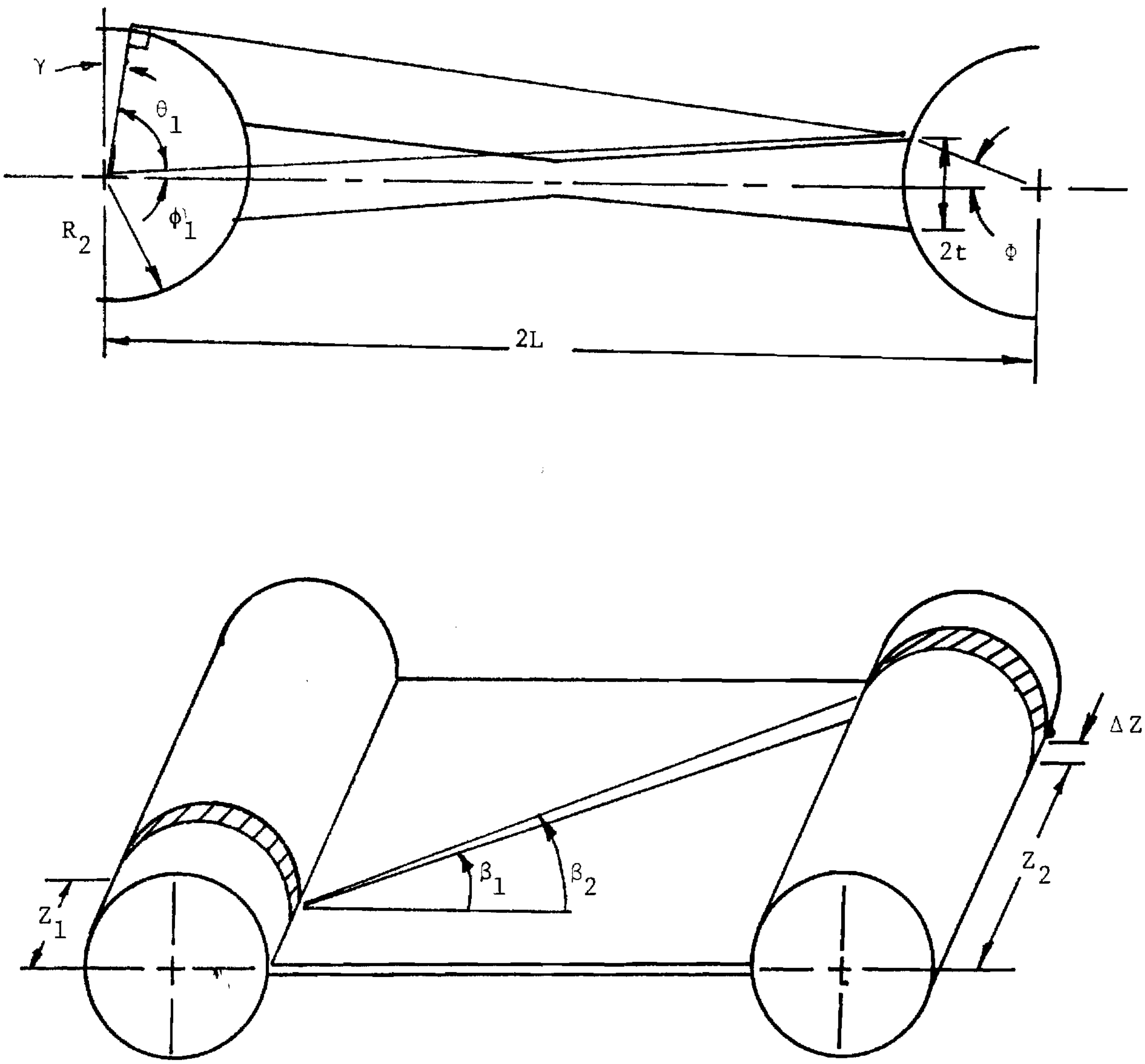


Fig. 5 Shape Factor Between Adjacent Tubes

$$WF = \int_{\beta_1}^{\beta_2} \cos^2 \beta d\beta = \frac{1}{2} (\beta_2 - \beta_1) + \frac{1}{4} (\sin 2\beta_2 - \sin 2\beta_1) \tag{D.15}$$

where

$$\beta_1 = \tan^{-1} \left[\frac{Z_2 - \Delta Z/2 - Z_1}{2(L-R_2)} \right]$$

$$\beta_2 = \tan^{-1} \left[\frac{Z_2 + \Delta Z/2 - Z_1}{2(L-R_2)} \right]$$

The shape factor between tube element is now

$$SS_{1-2} = \frac{WF}{\pi/2} F_{1-2} \tag{D.16}$$

where the valve for F_{1-2} is given by Eq. D.14.

BIBLIOGRAPHY

1. Schiller, Vortr. a.d. Geb. der Aerodynamik und verwandten Gebieten, Aachen, 1929.

2. Nikuradse, Forschangsheft No. 256, VDI

3. Techo, R., Tickner, R. R. and James, R. E., J. Applied Mech. Vol. 87, p. 443, June, 1965.

4. El-Wakil, M. M., Nuclear Power Engineering, McGraw-Hill, 1962, p. 255.

5. Hausen, H. Z. VDI, Beihefte Verfahrenstechnik, 1943, p. 91.

6. Kreith, F., Principles of Heat Transfer, 2nd. ed., p. 128.

7. Hottel, H. C. and Sarofim, A. F. Radiative Transfer, McGraw-Hill, 1967.

8. Armaly, B. F. and Tien, C. L., A Note on the Radiative Exchange Among Nongray Surfaces, Tran. ASME, Vol. 92, Series C, No. 1, Feb. 1970, p. 178.

9. Guard, F. L. and Schultz, H. D., Space Shuttle Aerodynamic Heating Considerations, ASME Paper No. 70-HT/SpT-16, June, 1970.

10. Eckert, E.R.G., Survey on Heat Transfer at High Speeds, WADC Technical Report 54-70 USAF Wright-Patterson AFB, April, 1954.

11. Shapiro, A. H., The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol. II., Ronald Press, New York, 1953.

12. Milton, J. F. and Schramm, W. B., Space Shuttle Vehicle Concept and Technology Requirements ASME Paper No. 70-HT/SpT-21, June, 1970.

13. Wallace, R. R., Jr.; Vinson, J. R. and Kornhauser, M., Effects of Hypervelocity Particles on Shielded Structures, American Rocket Society Paper 1683-61, 1961.

14. Rodriguez, D., Meteoroid Shielding for Space Vehicles, Aerospace Engineering Vol. 19, No. 12, December, 1960.

15. Radiator Design for Space Vehicles, Publication MS-AP-0069, Garrett Corp., Airesearch Mfg. Co., Los Angeles, Calif.

16. Cosby, W. A. and Lyle, R. G., The Meteoroid Environment and Its Effects on Materials and Equipment, NASA SP-78, 1965.

17. Wright, C. C., Thermal Analysis and Meteoroid Protection of Space Radiators, Air Force Report No. SSD-TR-66-98, June, 1966.

18. NASA Space Vehicle Design Criterion [Environment] Meteoroid Environment Model - 1969 [Near Earth to Lunar Surface] NASA SP-8013, March 1969.

19. Wulff, W. and Schipma, Design Guide for Pressurized Gas Systems, Task 7, NASA Contract No. NAS7-388, IITRI Report No. C6070-20, 1967.

20. U. S. Standard Atmosphere Supplements, 1966 U. S. Government Printing Office, Washington, D. C., 1966.

21. U. S. Standard Atmosphere, 1962, U. S. Government Printing Office, Washington, D. C., December, 1962.

22. Minzner, R.A., Champion, K. S. W. and Pond, H. L., The ARDC Model Atmosphere, 1959 AFCRC-TR-59-267, Air Force Cambridge Res. Center, August, 1959.

23. Keenan, J. H., and Kaye, J., Gas Tables, John Wiley and Sons, New York, 1945.

24. Champion, K. S. W. and Minzner, R. A., Proposed Revision of U. S. Standard Atmosphere 90 to 700 km., AFCRl-62-802, Air Force Cambridge Res. Labs., July, 1962.

25. Kopal, Z., Numerical Analysis, John Wiley and Sons, p. 195.

26. Keller, B. K., Numerical Methods for Two-Point Boundary-Value Problems.

27. Todd, Survey of Numerical Analysis, McGraw-Hill, 1962, p. 39.

28. Lieblein, Seymour "Analysis of Temperature Distribution and Radiant Heat Transfer Along a Rectangular Fin of Constant Thickness." NASA Technical Note D-196, Nov. 1959.

29. Black, W. Z. and Wulff, W., "Space Radiator Simulation--Manual for Computer Code," Final Report, Contract No. NAS9-10415, Georgia Institute of Technology, Atlanta, Georgia, April 1972.

30. Wulff, W., "Simplified Analysis and Optimization of Space Base and Space Shuttle Heat Rejection Systems," Final Report, Contract No. NASA-10415, Georgia Institute of Technology, Atlanta, Georgia, April 1972.